The Slope Water off the Scotian Shelf

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ABSTRACT

The slope water off the Scotian Shelf forms a well-defined band between the coastal waters and the Gulf Stream. Its boundaries fluctuate widely with no apparent systematics, sometimes transgressing upon the Shelf.

A survey in November 1951 indicates the presence of alternate bands of cold and warm water in the slope water and suggests that these are the direct result of instability in the northern edge of the Gulf Stream. Observed velocities support such a hypothesis. Temperature-salinity relationships indicate that the slope water is formed of waters from the surface layers of the Gulf Stream, surface coastal waters, Labrador waters and deep Atlantic waters which have upwelled under the Gulf Stream.

INTRODUCTION

WITHIN some 250 miles of the Nova Scotia Coast three distinctly different oceanographic regions are found. In sequence from the coast, they are the coastal water, the slope water and the waters of the Gulf Stream. The transition from one region to the next is not a gradual one, but involves the crossing of sharp boundaries where, within a very few miles, large variations in temperature and salinity take place. In an outward passage these transitions may usually be recognized from temperature observations alone. Sometimes, however, as will be illustrated, observations of salinity must be added to locate with surety the boundary between slope and coastal waters.

The most typical feature of the coastal waters is the three-layer system described by Hachey (1942). The upper layer, of comparatively low salinity, displays great variation in temperature with the seasons. The salinity of this layer increases outward from less than 30‰ to approximately 33‰, and temperatures are generally higher offshore than at the coast. The intermediate layer appears, throughout the greater part of the year, as a layer of minimum temperatures, generally less than 5.0°C. This layer results from waters which flood the area from the northeast (Hachey, 1938), and is often divided into two distinct phases by the outer banks (McLellan and Trites, 1951). Inshore, the coldest water in the intermediate layer is associated with a salinity of approximately 32.5‰, while beyond the outer banks it displays salinity very close to 33.0‰. The deep layer in the coastal water region is warmer and more saline than the intermediate layer and is present only beyond the outer banks and over the deeper portions of the shelf.

The term "slope water" seems first to have been introduced by Bjerkan (1919) in describing the waters of the Scotian Shelf. He classified waters entirely on the basis of salinity, slope water being between 33.0‰ and 35.0‰. Huntsman (1924) and Bigelow (1927) subsequently spoke of the waters just

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beyond the shelf as "slope water" and Iselin (1936) applied the term to "the band of water between the edge of the continental shelf and the Gulf Stream". In this article the term "slope water" will be used in the sense of Iselin's definition although the inner boundary will be designated by oceanographic, rather than topographic, features. In most temperature profiles running outward from the Scotian Shelf, a region is observed where, with the usual scale distortion, a band of closely spaced isotherms appears virtually vertical. Here the three-layer system of the coastal waters gives way to a less regular temperature distribution which may or may not exhibit minimum temperatures at intermediate depths. The transition, which may take place in two miles or less, is accompanied at the surface by a sudden rise in temperature and an abrupt increase in salinity to over 34.5‰. This region we have called the slope-water boundary and designate it as the transition between coastal and slope waters.

The slope water, by definition, ends at the inner edge of the Gulf Stream. Here again, the isotherms slope precipitously downward as temperatures at all levels rise. The Gulf Stream exhibits a very deep mixed layer of high temperature and salinity lying over deep waters whose T-S characteristics are those of Central Atlantic waters (Iselin, 1936). The strong current towards the north and east, as well as a rise in surface temperature and salinity, marks the boundary between the slope water and Gulf Stream.

<center>OBSERVATIONS</center>

NATURE OF THE SLOPE WATER

In temperature and salinity the surface layers of the slope water lie intermediate between the coastal waters and the Gulf Stream. That the slope water represents an area of mixing is emphasized by the occurrence of large patches of water sometimes colder and sometimes warmer than their surroundings. Examples of this will be given below. Apparently quantities of both coastal and Gulf Stream waters are continually breaking away from their respective regions and becoming mixed into the surface layers of the slope water as was suggested by Iselin (1936, p. 11).

As pointed out by Iselin (1936, p. 38), the deeper slope water falls on a T-S curve which closely parallels the curve representative of Central Atlantic water. Points on the slope-water curve, however, indicate water types similar to those found at 200 to 600 metres greater depth in the Central Atlantic. If this represents upwelling under the Gulf Stream it is consistent with the picture that Rosby (1936) draws from the application of the wake-stream theory to the Gulf Stream system. Rosby (1936, p. 32) has concluded that the agreement between Sargasso Sea and slope-water T-S curves is sufficient to show "that coastal and northerly waters play a minor role in the production of slope water". The fact remains, however, that the slope-water observations fall consistently on such a curve where water of any temperature is measurably less saline than in the Central Atlantic. Either these "similar" waters are formed in surface-layer mixing, or coastal waters must mix with the deep waters upwelled under the Gulf Stream to form the deeper slope waters.

If the wake-stream theory is to be applied to the Gulf Stream system off Nova Scotia, it would be expected that the slope water represents the region of counter-current. The theory of a counter-current seems to be widely held although there is a lack of data pointing to its existence. Conversely, the evidence in favour of strong currents toward the northeast in the slope water is impressive. Sandstrom (1919), from observations made in the summer of 1915, computed currents normal to hydrographic sections running outward from the Nova Scotia coast. Over the shelf, velocities were generally low and towards the southwest. In his section VIII, which ran well into the slope water, a band of water, centred some 20 to 40 miles outside of the slope-water boundary, displayed a velocity of over half a knot in a northeasterly direction, while waters on either side moved towards the southwest. These velocities from Sandstrom's dynamic calculations are shown in Figure 1, together with observed surface temperature and salinity. It
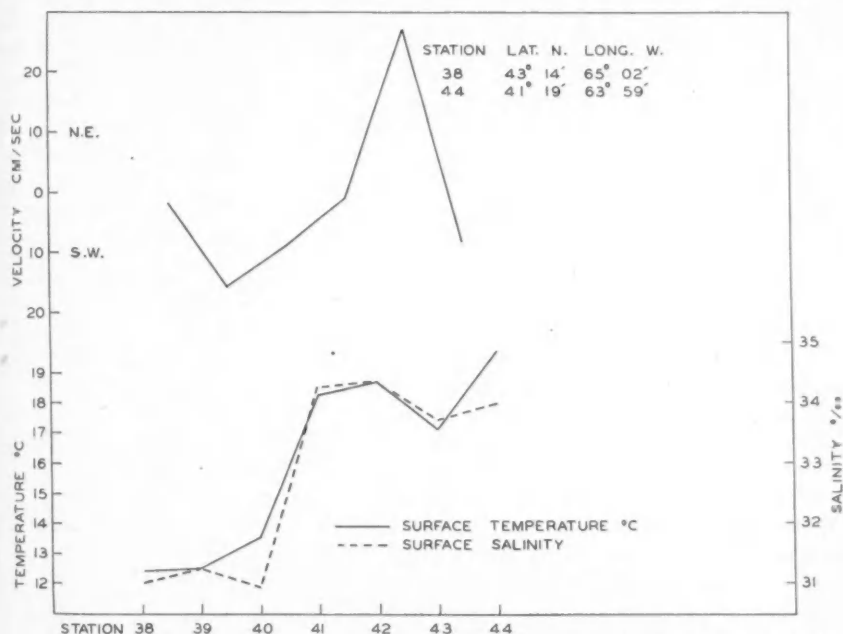

FIGURE 1. Surface temperature, surface salinity and computed velocities from *Acadia* stations 38 to 44, July 21st and 22nd, 1915.

may be seen that the slope-water boundary fell between stations 40 and 41, while the high northeasterly velocity appeared between stations 42 and 43. Fuglister (1951) has interpreted temperature observations to show the existence of multiple currents in the Gulf Stream system, inferring one or more currents in the slope water paralleling the main stream. The November 1951 data, to be discussed later, showed measured velocities up to 0.7 knots to the northeast. All this seems to point to northeasterly currents as a regular feature of the slope water.

THE SLOPE-WATER BOUNDARY

The slope-water boundary, as we shall designate the inshore edge of the slope-water regime, has been described above. It represents only the temporary limits of the shoreward extent of the slope water. The position of the boundary is variable over wide limits, sometimes lying far beyond the shelf and at other times being observed to transgress upon the shelf itself. Thus, on the outer banks of the Scotian Shelf, there is a conflict between warm, saline slope waters and the cold, less saline waters which usually flood the area from the northeast (Bigelow, 1927; Hachey, 1938). For this reason some knowledge of the origin and behaviour of the slope water is essential to an understanding of the oceanography of the Scotian Shelf.

In most cases the slope-water boundary appears to be nearly vertical, and a rise in surface temperature and salinity occurs in the same location as a nearly vertical 10°C. isotherm which divided the water masses down to 250 metres or more. At times, however, during the winter months, there have been incursions of the deeper slope water onto the shelf (Hachey, 1949; McLellan and Trites, 1951) with the result that the boundary slopes shoreward from top to bottom. Two criteria have been applied in assigning a geographical position to the slope-water boundary from any section of observations. When temperature observations alone have been available, the boundary has been taken as the most shoreward position at which the minimum temperature above 250 metres has been over 10°C. When surface temperature and salinity have been observed, the boundary has been taken to be that point at which both rise abruptly.

In Figure 2 all positions at which the slope-water boundary has been observed in data on file with the Atlantic Oceanographic Group, up to and including November 1951, are plotted (open circles). Where two or more observations have been made in a single month, their positions have been joined and the month indicated to show a possible configuration of the slope-water boundary. Fifty-five crossings are recorded, the majority lying between 60° and 65° West Longitude. Of these the most southerly was at 40° 16' North Latitude in May 1950, and the most northerly at 43° 11' North Latitude in November 1950.

Crossings of the northern edge of the Gulf Stream from the same cruises have also been shown in Figure 2 (solid circles). Where two or more of these observations have been made in a single month they too have been joined to show a possible configuration of the Gulf Stream's northern edge.

From the plotted data it may be seen that:

1. The position of the slope-water boundary is subject to wide variations which do not appear to be systematic. At 64° West Longitude a north-south variation of 150 miles has been observed. The fact that incursions of slope water upon the shelf have been observed mainly during the winter months points to a possibility that the slope water moves inshore at that time. However, the inshore position of the boundary in July 1949 argues against such a seasonal effect. More data are required before the systematics of the variations can be conclusively stated.

2. The width of the slope-water regime, as shown by concurrent positions of the slope-water boundary and the northern edge of the Gulf Stream, varies greatly. For example, a width of less than 20 miles was observed in June 1950—and a width of over 120 miles in November 1950.

3. The limits of positions observed for the slope-water boundary and for the northern edge of the Gulf Stream overlap by as much as 80 miles.

4. The configuration of the slope-water boundary does not necessarily follow that of the Gulf Stream edge.
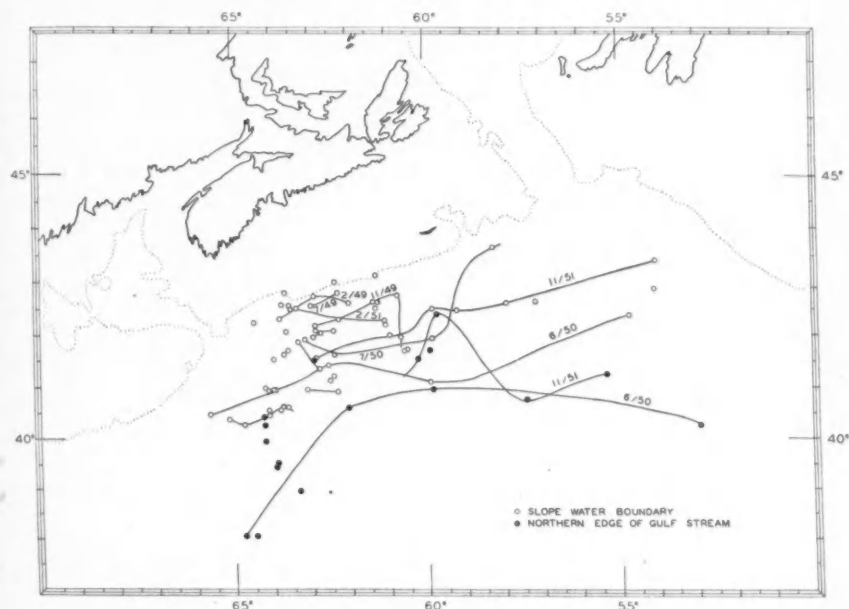
FIGURE 2. Observed positions of the slope-water boundary and of the northern edge of the Gulf Stream, up to and including those of November 1951.

SLOPE-WATER INCURSIONS ON THE SCOTIAN SHELF

The existence of warm, saline slope waters just beyond the Scotian Shelf provides a source for periodic flooding of the outer banks with waters of quite different characteristics from those generally found there. Such floodings were observed by Hachey (1949) in February 1949 and again during January and February 1951 (McLellan and Trites, 1951).

The mechanism by which these changes take place is illustrated in Figure 3. The T-S relations for stations 22, 23, 24 and 24A of *Whitethroat* cruise No. 6 in February 1951, a series of stations running southeasterly from the edge of the shelf (station 22, Latitude 43° 11′ N., Longitude 62° 06′ W.) to the deeper water beyond (station 24A, Latitude 42° 17′ N., Longitude 61° 04′ W.), are shown.

The depth, in metres, of the observations is indicated opposite each point. The grouping of all upper-layer observations along a straight line indicates that horizontal mixing takes place between the cold, low-salinity surface water over the banks and the comparatively warm, saline, surface slope waters. By reference to the indicated depths it can be seen that this mixture sinks and flows shoreward under the less dense surface shelf waters. Water which, from its T-S characteristics, is composed in equal parts of surface waters from stations 24 and 24A is found at 30 metres depth at station 24 and at 65 metres depth at station 23. Similarly, water found at 20 metres at station 24 is found at 50 to 75 metres at
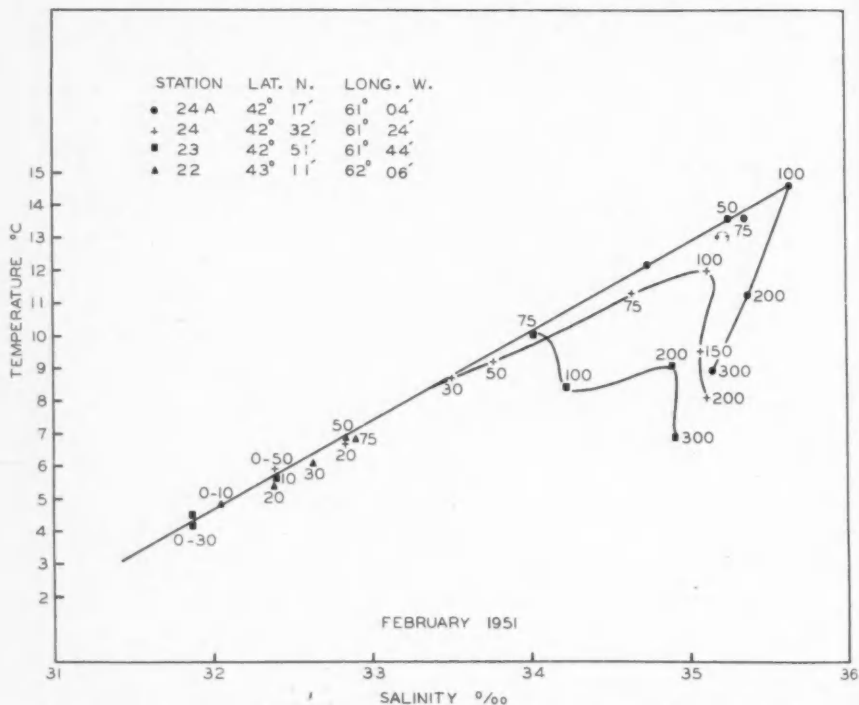
FIGURE 3. Temperature-salinity relationships for stations 22 to 24A, February 1951. Numbers indicate depths of observations in metres.

station 22. It would appear that surface coastal waters, perhaps assisted by the prevailing northwest winds of winter, move offshore and are consumed in horizontal mixing, and that this offshore movement is accompanied by a shoreward flow of the mixed waters. An isolated warm-water mass which has probably been formed in this manner is sometimes observed lying against the continental slope beyond the outer banks (McLellan and Trites, 1951).

A more spectacular type of incursion was observed in August 1950 and related to the passage of a severe storm (McLellan and Trites, 1951). Two tem-

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FIGURE 5. Vertical temperature distribution from Lat. 43° 03'N., Long. 64° 09'W., to Lat. 41° 34'N., Long. 62° 55'W., 29th November 1951.

were combined with standard hydrographic sampling according to the fixed plan for seasonal cruises (McLellan and Trites, 1951). Beyond the regular pattern, except for five scattered hydrographic stations, B.T. observations alone were made so as to facilitate electromagnetic current measurements with a G.E.K. (von Arx, 1950). The vertical temperature distribution as observed during this cruise has been plotted in profile for each of the six crossings of the slope water, and is shown in Figures 5 to 10 inclusive. The sections plotted have been lettered A to F in Figure 4. Observations on the shelf itself have been mostly omitted from these figures.

(*a*) VERTICAL TEMPERATURE DISTRIBUTION

Section A, Figure 5, running outward from LaHave Bank, showed an intrusion of warm water between observations 169 and 172, having temperatures over 17.0°C. at 50 metres, at observation 171, and surface maxima in temperature (14.0°C.) and salinity (33.95‰) at 172. The main slope-water boundary was observed in the subsurface layers at observation 176, and at the surface between 178 and 179. Here, in less than two miles, the surface salinity increased from 33.85‰ to 34.82‰.

Figure 6 shows the vertical temperature distribution running out over
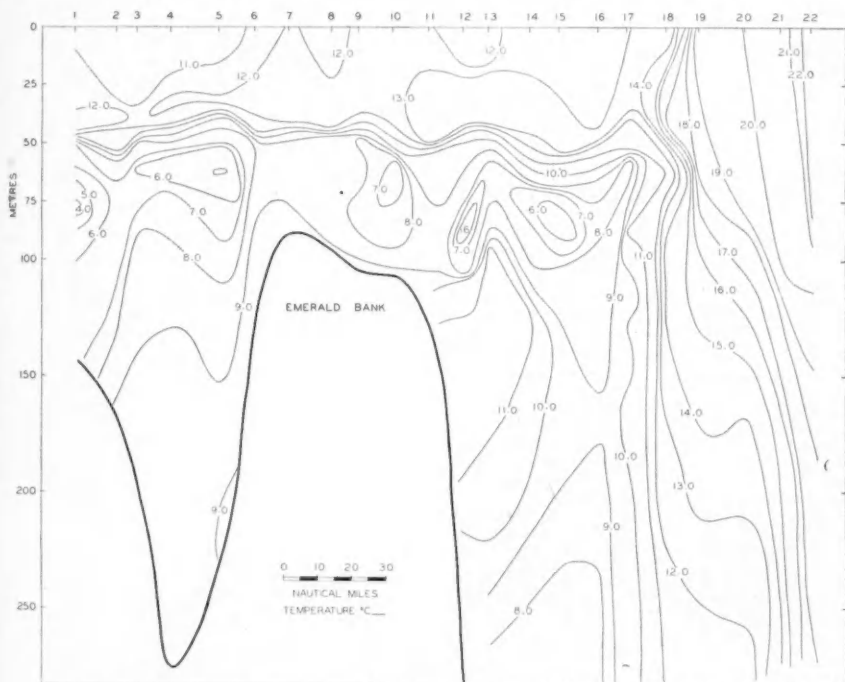
FIGURE 6. Vertical temperature distributions from Lat. 44° 17′N., Long. 63° 20′W., to Lat. 41° 33′N., Long. 60° 18′W., 12th and 13th November 1951.
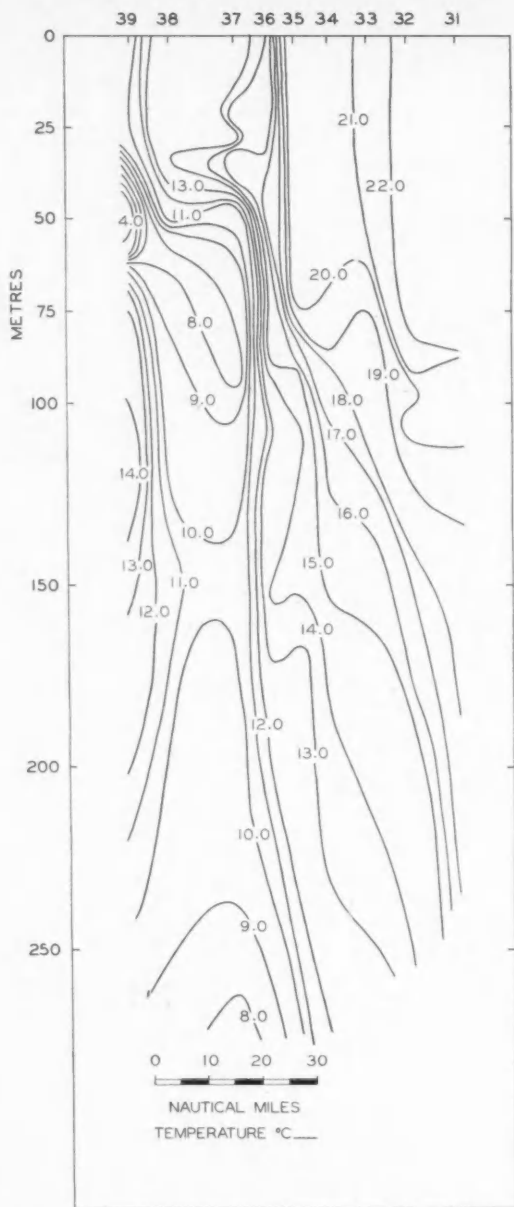
FIGURE 7. Vertical temperature distribution from Lat. 42° 56′N., Long. 59° 51′W., to Lat. 41° 56′N., Long. 59° 51′W., 14th November 1951.

Emerald Bank as far as the Gulf Stream (section B). A fairly typical temperature structure in the coastal water was displayed, with distinct temperature minima in the intermediate layer. This layer was divided into two phases by Emerald Bank. The body of warm water (over 11°C.) lying against the edge of the shelf was likely the remnant of a water mass formed in the manner discussed above under slope-water incursions. The slope-water boundary was here quite distinct between observations 18 and 19, where surface salinities rose suddenly from 33.5‰ to 35.7‰. Thirty-five miles beyond the slope-water boundary, the northern edge of the Gulf Stream was crossed at observation 22.

The next section to the east (section C) is shown in Figure 7. This short section ran south from a point somewhat off Sable Island. Here the slope water lay in a band less than 25 miles wide from the slope-water boundary between observations 35 and 36 to the Gulf Stream edge at observation 32.
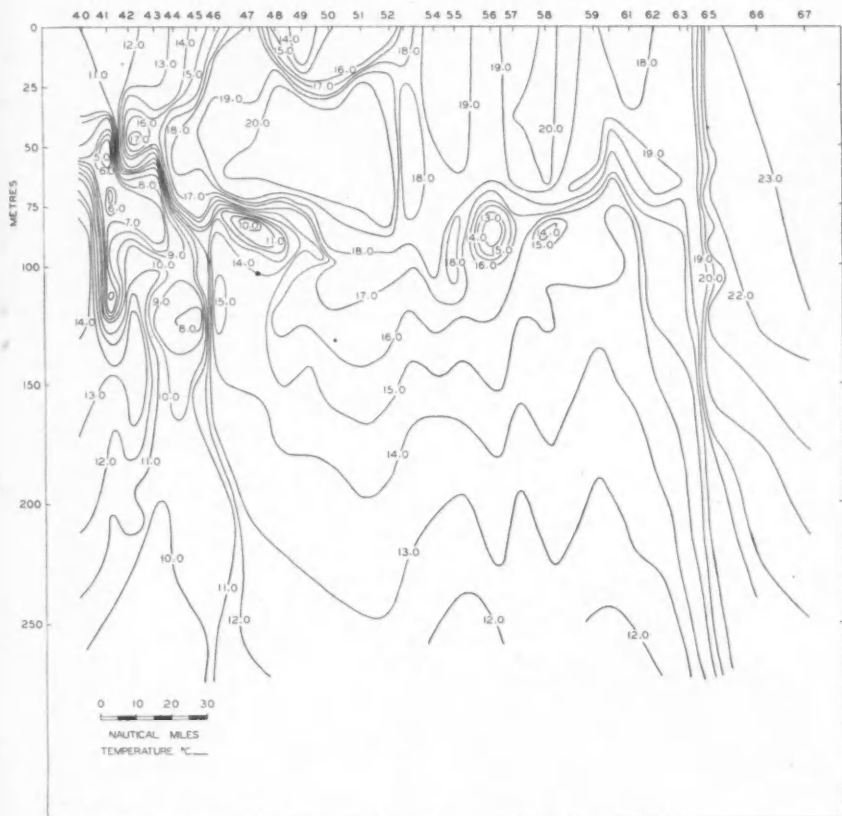
FIGURE 8. Vertical temperature distribution from Lat. 42° 56'N., Long. 59° 48'W., to Lat. 40° 35'N., Long. 56° 45'W., 14th and 15th November 1951.

Figure 8 shows section D which ran outward at a small angle to section C (Figure 7). Here the slope-water boundary fell near observation 46, although a fold of cold water (less than 10°C.) protruded some 20 miles beyond at the 80-metre level. This section ran just east of a shoreward bulge in the Gulf Stream, and 120 miles of slope water were traversed before the Stream was entered at observation 65. Two centres of cold water were observed in the slope water in this section at a depth of about 75 metres.
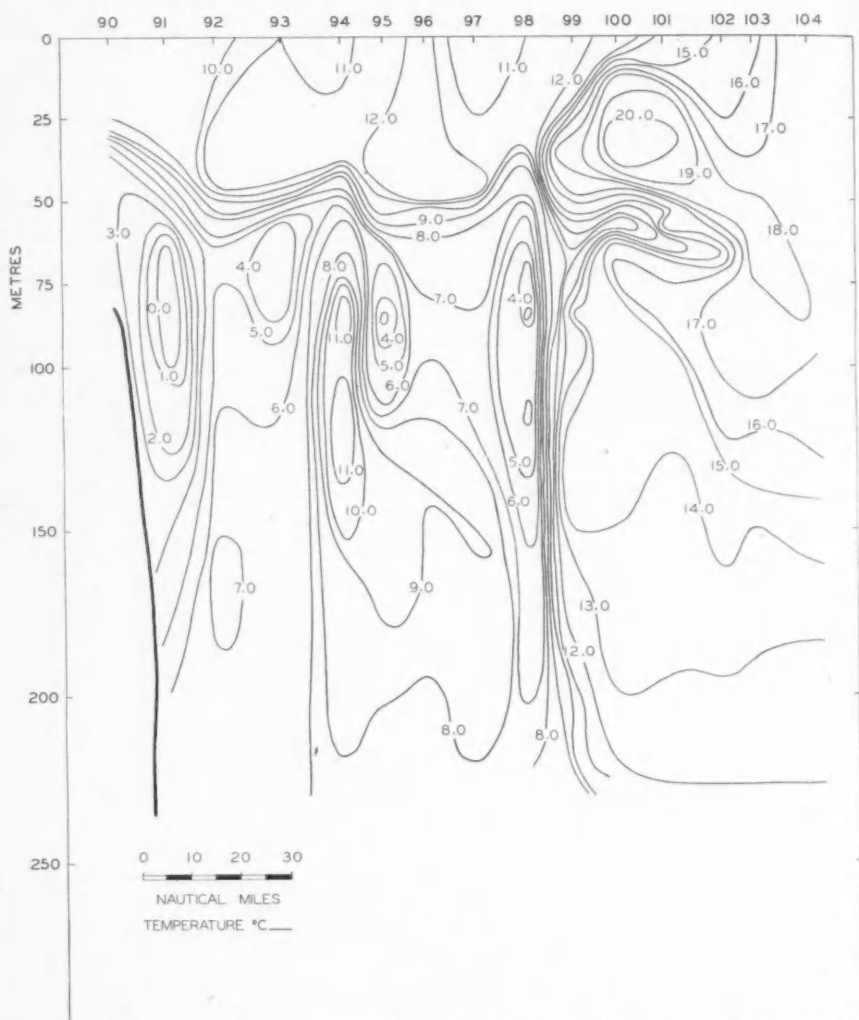
FIGURE 9. Vertical temperature distribution from Lat. 44° 14′N., Long. 58° 18′W., to Lat. 42° 04′ N., Long. 57° 52′W., 13th November 1951.

Section E in Figure 9 ran due south from Banquereau Bank. Here, in the coastal-water regime, water with temperature less than 0.0°C. was found close against the shelf edge. Four distinct centres of cold water, and a body of water warmer than 11.0°C., were found inshore from the slope-water boundary. The boundary, from a temperature criterion alone, was found at observation 99, although a shallow layer of low salinity water ran farther seaward so that the discontinuity in surface salinity was observed between 103 and 104. A body of cold water pushing into the slope water at the 60-metre level appeared to be continuous from the previously discussed section, over 50 miles to the west. This section did not extend to the Gulf Stream.

Figure 10 shows section F which ran southwest from the Grand Banks near Whale Deep. A large body of cold water with temperatures as low as —0.9°C. was found just beyond the shelf. This cold water appeared to lie in two distinct bands and to be flanked by a marked transition zone or slope-water boundary between observations 95 and 97. Beyond this over 150 miles of slope water lay inside the Gulf Stream. Through this slope water ran alternate zones of cold and warm waters at the 50- and 75-metre levels.
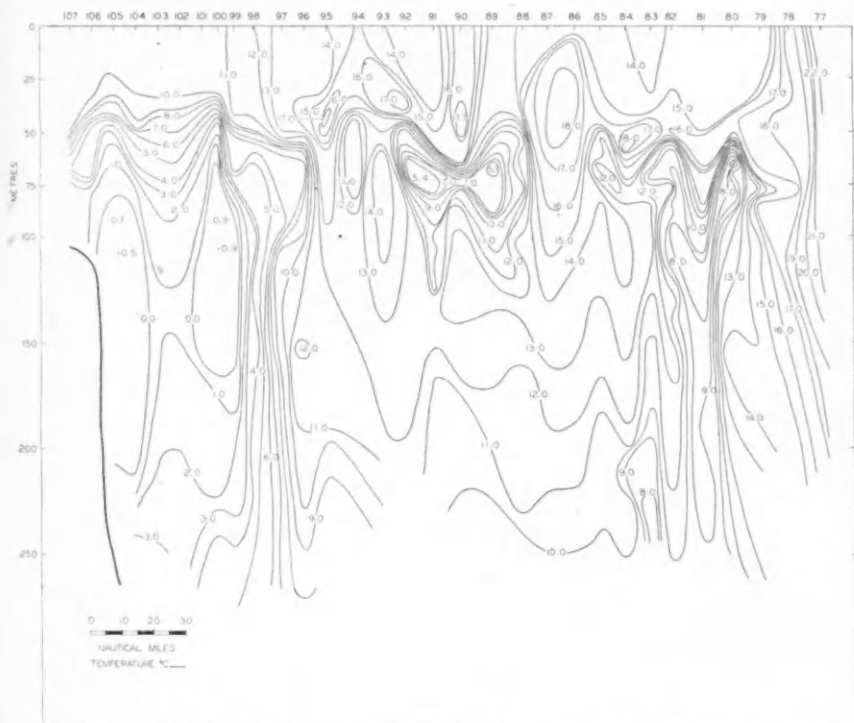
Figure 10. Vertical temperature distribution from Lat. 44° 33'N., Long. 53° 06'W., to Lat. 41° 10'N., Long. 55° 32'W., 15th to 17th November 1951.

(b) HORIZONTAL DISTRIBUTION OF MINIMUM TEMPERATURE

The occurrence, in many temperature sections through the slope water, of zones of cold water, and, in particular, the similarity in structure of cold zones in adjacent sections, lead to the conception that these zones indicate long bands which lie parallel to the coast and thus perpendicular to most sections. With this preconceived idea of the nature of the cold-water distribution, Figure 11 has been constructed. It shows in plan the minimum temperatures occurring above 100 metres for all the area surveyed in November 1951. It should be borne in mind that a quite different distribution could be depicted from the same data by one convinced of the patchy nature of cold zones as opposed to a tongue-like configuration. The thesis is presented here that the tongue-like configuration of cold-water bands is a necessary feature of the slope water and that it illustrates one of the mechanisms by which the surface slope waters are generated.
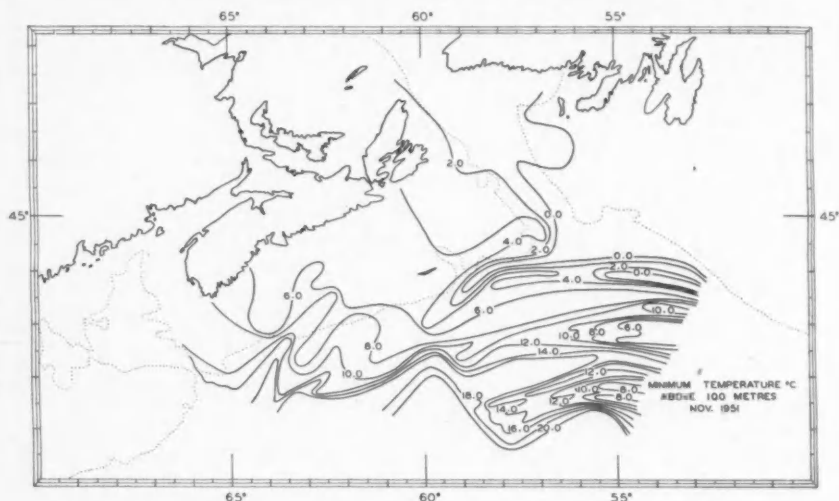
FIGURE 11. Distribution in plan of the minimum temperature above 100 metres as observed during November 1951.

(c) VELOCITIES OBSERVED IN NOVEMBER 1951

During part of the November 1951 cruise, H.M.C.S. *New Liskeard* made electromagnetic current measurements with a G.E.K. (von Arx, 1950). The component velocities normal to the ship's track for certain of these measurements have been plotted in Figures 12 and 13, along with the corresponding minimum temperatures found above the 100-metre level.

Figure 12, covering the same crossing as the temperature section in Figure 8, shows a northeast velocity of over 0.7 knots coincident with the first marked rise in temperature. Thereafter the currents fluctuated widely without good correlation to temperature, until a drop in temperature, just before the Gulf Stream was

entered, was accompanied by a reversal of velocity to about 0.4 knots towards the southwest.

Figure 13 shows the section running southward from the Grand Banks. Here again there was an inshore peak in the eastward velocity (0.7 knots) which coincided with a peak in minimum temperature. There were slight westward velocities indicated on either side of this peak which followed low minimum temperatures, then the correlation was scant until the crossing into the Gulf Stream.

At this time, then, there existed a current flowing in the slope water with a direction similar to that of the Gulf Stream and velocity of at least 0.7 knots. If a counter-current were present at all it was as a narrow band of cold water close against the Stream.

THE ORIGIN OF BANDS IN THE SLOPE WATER

The Gulf Stream curves away from the continental shelf near Cape Hatteras and passes off Georges Bank, the Scotian Shelf and the Grand Banks as a high-velocity, well-defined, current. As it leaves Hatteras, the Stream begins to
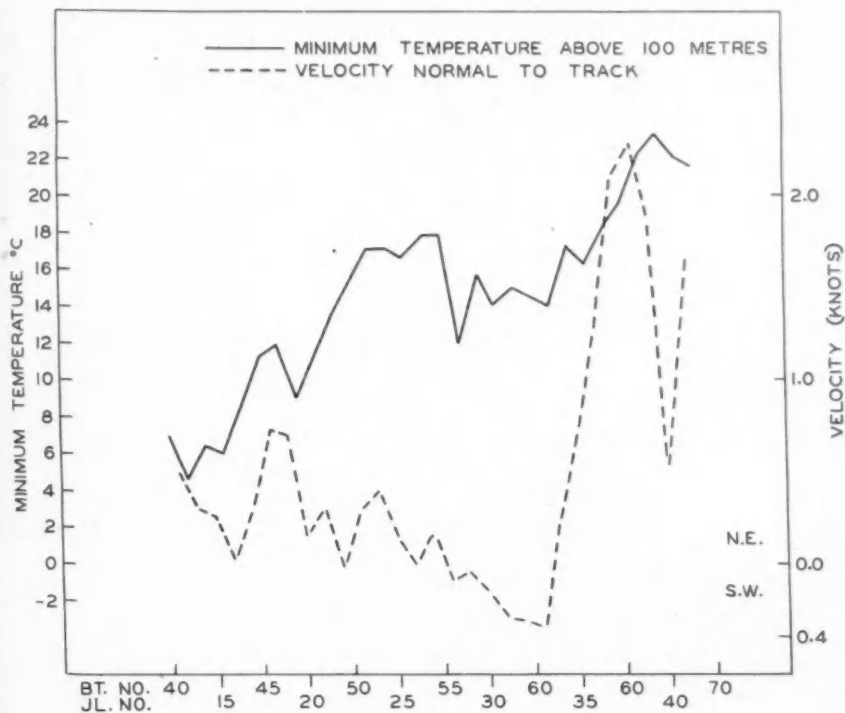
FIGURE 12. Minimum temperature above 100 metres and velocity component normal to ship's track from Lat. 42° 56′N., Long. 59° 48′W., to Lat. 40° 35′N., Long. 56° 45′W., 14th and 15th November 1951.
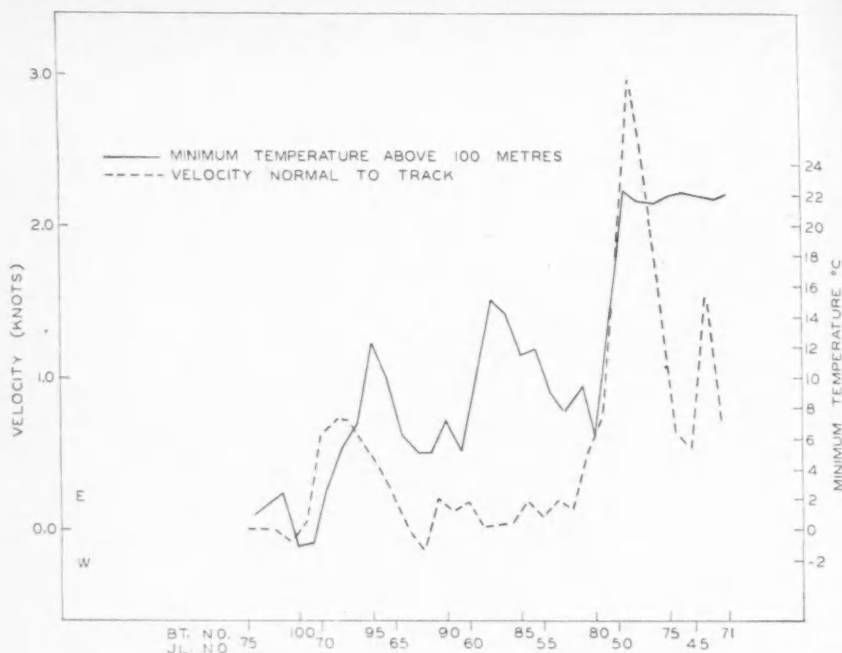
FIGURE 13. Minimum temperature above 100 metres and velocity component normal to ship's track from Lat. 44° 34′N., Long. 53° 06′W., to Lat. 40° 37′N., Long. 56° 18′W.

meander, so that its northern boundary assumes a wave-like configuration. It has been shown (Haurwitz and Panofsky, 1950) that, as the sheer zone moves away from the continental slope, it becomes unstable to oscillations of the longer wave lengths, so that perturbation of such wave lengths will grow in amplitude along the Stream. The conditions for instability are especially well filled in the oceanic triangle between the Grand Banks and the Scotian Shelf, where the Gulf Stream must seldom lie less than 150 miles from the continental slope. Consider a well-defined wave in the Gulf Stream (as illustrated by the configuration of the 18° and 20°C. isotherms in Figure 11) travelling eastward through this area with increasing amplitude and passing the tail of the Grand Banks. Frigid waters from the Labrador Current creep around the tail of the Grand Banks and spread along the outer edge of the Scotian Shelf as far as Banquereau. As each wave crest passes the tail of the Banks, as shown schematically in Figure 14, there will be a tendency for cold water to be drawn down into the wake of the retreating crest. At the same time the next crest advancing into the area will be driving slope water shoreward and along its direction of advance. In this way, as successive waves pass through the area, it can be appreciated how a series of alternate bands of warm and cold water would be established, with the resultant accelerated mixing of coastal and Gulf Stream waters.

FIGURE 14. Schematic illustration of the production of cold-water tongues in the slope water by the passage of waves in the Gulf Stream.

The passage of progressive waves along the Gulf Stream will tend to impart to the slope waters an overall velocity in the direction of wave propagation and of magnitude up to that of the wave velocity. Haurwitz and Panofsky (1950) have shown that this wave velocity may, under proper conditions, approach 50 per cent of the stream velocity. This, together with the mechanism pictured above, may well give rise to the type of multiple-current system visualized by Fug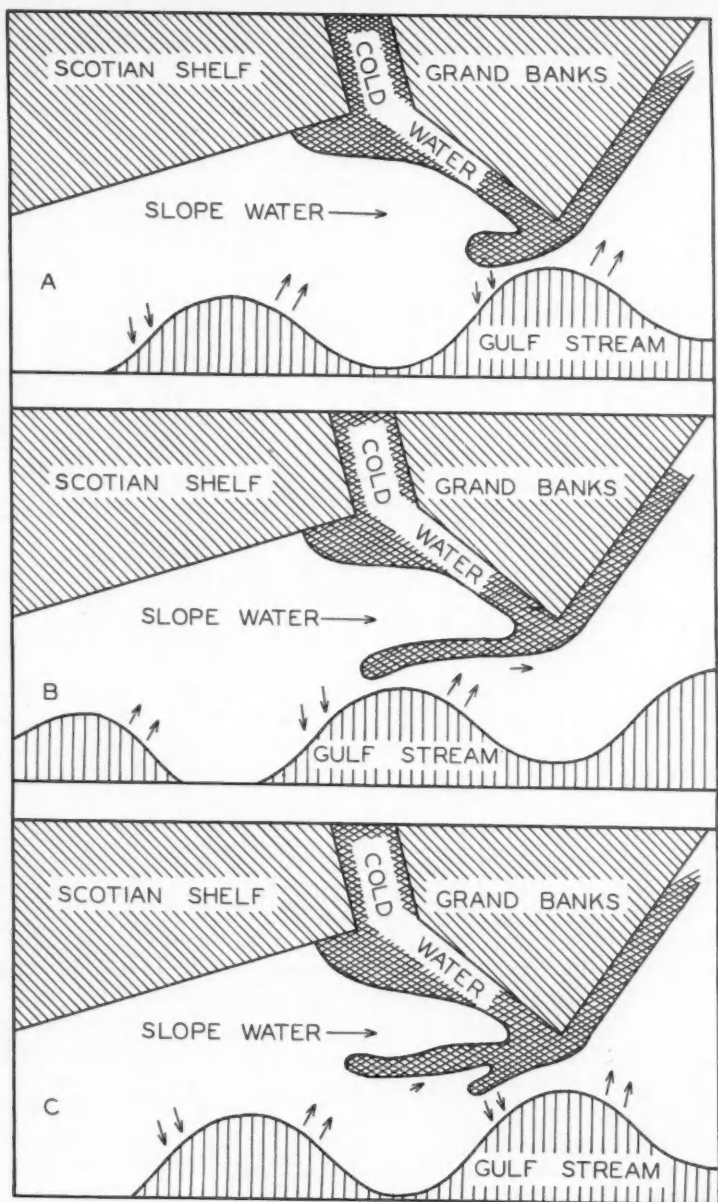lister (1951). Bands of slope water, to which eastward velocities have been imparted by the passage of waves, are forced between cold-water bands which have residual westward velocities, and thus the warm waters are constricted into more narrow bands with higher velocities.

The failure of the Labrador Current to round the tail of the Grand Banks as a strong current may be accounted for by two phenomena associated with instability of the Gulf Stream. First, the passage of each wave in the Gulf Stream edge will draw a large body of the cold water into the slope-water region where it is consumed in the production of slope water. Secondly, the eastward velocity impressed on the slope water by the passage of these progressive waves is in conflict with the westward flow of Labrador water.

HORIZONTAL MIXING

The T-S curves for selected stations occupied during November 1951 (Figure 15) give a picture of the way in which the slope water is formed. The curve lying to the lower right of the figure represents the characteristics of Central Atlantic waters deeper than 400 metres (Iselin, 1936). Stations 25 and 70, taken well within the Gulf Stream, illustrate surface-layer T-S relationships there. The deeper waters at these stations fall almost exactly on Iselin's curve, though water found at 600 metres in the Sargasso Sea was found at 400 metres at station 25. Station 31 is representative of the deeper coastal stations, and station 120, off the Newfoundland Coast, shows the full development of the cold intermediate layer. The other stations belong to the slope-water regime or the outer fringe of the coastal waters.

At the surface, all observations lay close to a straight line running from the surface characteristics of the most coastal (station 31) to those of the Gulf Stream stations (station 25), indicating that direct mixing of these waters takes place. The observations at 30 metres at stations 24 and 32A fell on this same line, and each was warmer and more saline than the corresponding surface waters. This shows that some of the water formed by surface mixing sinks and flows shoreward under the lighter, more coastal waters.

A definite bend in the T-S curves of all but the most seaward stations indicates the influence of the cold-water layer.

The deep waters of all stations have T-S characteristics which fall on a smooth curve that nearly parallels Iselin's curve for Central Atlantic water. The depth at which these water types occur, however, is much less than that at which similar types are found in the Sargasso Sea. Water closely resembling that found at 1000 metres in the Sargasso Sea is found at 400 metres in the slope

water. Iselin (1936) has remarked upon this apparent upwelling and the fact that water of a given temperature is less saline in the slope water than in the Central Atlantic.

A straight line drawn from $T = 1.3°C.$, $S = 32.95‰$, a point representative of the core of the cold water, to a point representative of similar depths in the Gulf Stream (19.0°C. and 36.6‰) falls along a section of the deep-water curve paralleling Iselin's Central Atlantic curve. Here, then, we have two types of water, with approximately the same density, efficiently mixed to produce waters of greater density which sink and flow under the lighter waters. The subsurface layers of the slope water must be formed in this way, and by a mixture of waters so formed with Central Atlantic waters, upwelled against the continental slope. For example, the water of 400 metres under station 32 would appear to be formed from mixed intermediate waters and water of the type found at approximately 1300 metres in the Central Atlantic.
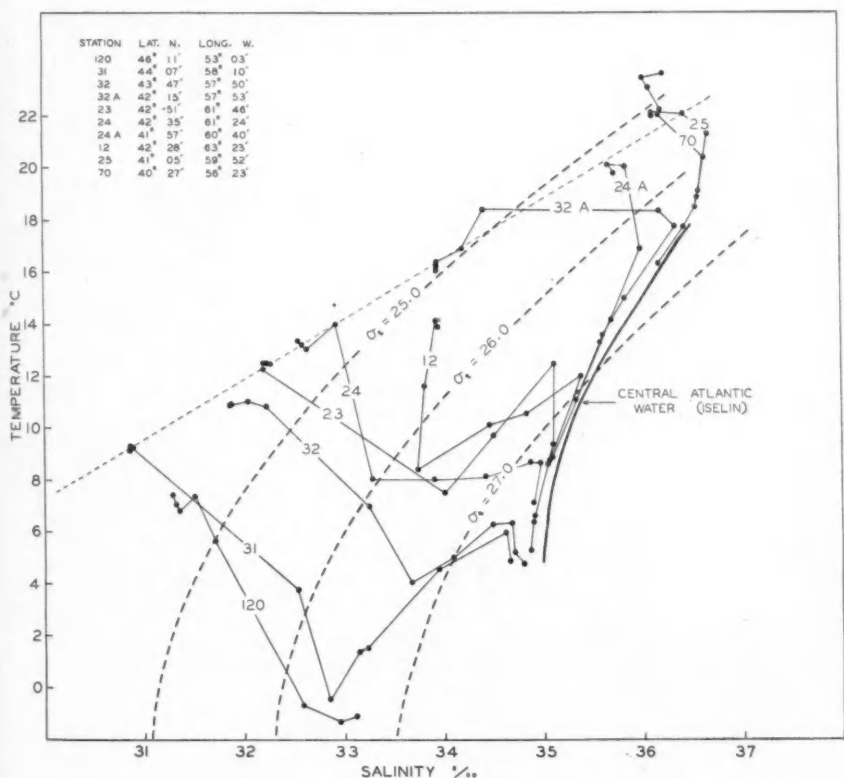
FIGURE 15. Temperature-salinity relationships for selected stations occupied during November 1951.

Figure 16 depicts schematically the formation of the slope water. The region is pictured as one of intense internal mixing brought about by sheer zone turbulence and the large-scale eddies produced by meanders or waves of the Gulf Stream. This diagram shows the mixing area as a single band lying between the coastal waters and the Gulf Stream. It would be perhaps more realistic to think of a series of bands of water having properties intermediate between these extremes, with intense mixing taking place between adjacent bands.

The deepest water at the inshore stations is shown as being formed by a mixture of cold water and water found in the very deep Central Atlantic. This is consistently shown by T-S relationships for waters as far inshore as the deep channel of Cabot Strait.
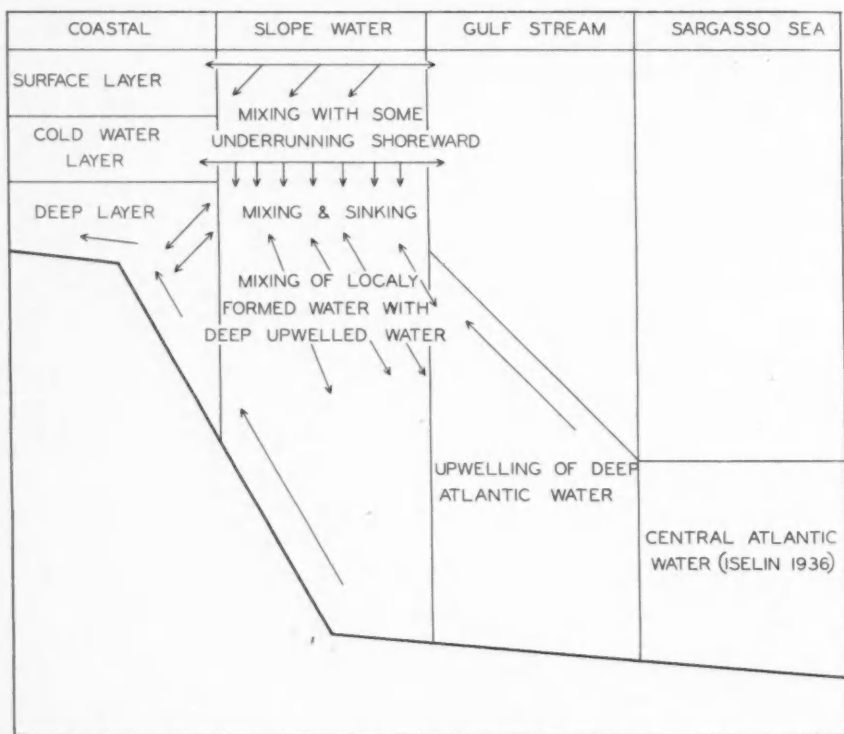
FIGURE 16. Schematic diagram showing the way in which slope water may be formed.

DISCUSSION

The consideration of the slope-water regime as a region of mixing between coastal and Gulf Stream waters presents a logical explanation of its formation which is well substantiated by temperature and salinity observations. The fact that some, at least, of the deeper slope water could be formed from a mixture of

cold intermediate shelf water, and Gulf Stream waters from similar depths, helps to explain the consistent T-S characteristics of these waters. However, upwelling of Central Atlantic waters, and their mixture with others formed in the slope-water regime, must be invoked for a full explanation of the deep T-S relationships.

Such a picture of a region of turbulent mixing, lying as a "buffer" between the meandering Gulf Stream, and coastal waters which are mostly shallow enough to respond to meteorological factors, gives little hope that transport could be calculated. However, some qualitative ideas concerning the resultant motion can be formed. In Figure 16 the slope water region has been shown as receiving water by horizontal mixing from all levels of the shelf water, and from the surface layer of the Gulf Stream. It also shows water upwelling from the deep layers of the Central Atlantic. The only indication of water leaving the slope region is in the production of deep coastal waters which can not regularly consume any large volume of water. Coupled with this, the fact that the slope water is found only as far south as Cape Hatteras, points to a regular flow of slope water towards the northeast. The existence of such a flow is indicated in the velocity profiles of Figures 12 and 13 and is consistent with the concept of multiple currents in the Gulf Stream system as visualized by Fuglister (1951).

SUMMARY

1. (a) Off the Scotian Shelf the transition from coastal to slope water is a well-defined boundary easily recognized in a vertical section of temperature and salinity observations.

(b) The position of this slope-water boundary is subject to wide variations which do not appear to be systematic.

(c) The width of the slope-water regime may vary from over 120 to less than 20 miles.

(d) The limits of observed positions for the slope-water boundary and the northern edge of the Gulf Stream overlap by up to 80 miles.

(e) The configuration of the slope-water boundary does not necessarily follow that of the northern edge of the Gulf Stream.

2. Incursions of slope water upon the Scotian Shelf frequently take place. One mechanism which brings about these incursions involves surface mixing at the boundary with a shoreward movement of the denser mixture under the light surface coastal waters. In one case, the passage of a severe storm through the area brought about a marked incursion.

3. An extensive two-ship survey of the area in November, 1951, showed alternate bands of cold and warm water in the slope water. These are probably formed by the interaction of progressive waves in the unstable northern edge of the Gulf Stream with the flow of Labrador water around the tail of the Grand Banks. Consistent with such a hypothesis are the observed northeastern velocities in the slope water.

4. Temperature-salinity relationships observed in November, 1951, show the slope water to be formed in the following way:

(a) Upper layers by mixture of coastal and Gulf Stream surface waters.

(b) Intermediate depths from a mixture of cold Labrador waters with subsurface Gulf Stream waters.

(c) Deeper waters from Central Atlantic waters which have upwelled under the Gulf Stream and have been more or less modified by waters formed as in (b).

5. These observations are not inconsistent with the recently proposed concept of multiple currents in the Gulf Stream system.

ACKNOWLEDGEMENTS

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Certain Aspects of Oceanography in the Coastal Waters of Labrador

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ABSTRACT

Oceanographic study of six inlets along the Labrador coast shows that their water comes primarily from the cold Labrador current. Below 50 meters, temperatures are characteristically below zero, and salinities usually between 32 and 33‰. The principal exception is Lake Melville, which, although below zero, is very slightly warmer and freshened to 26–29‰. In summer there is some freshening and warming of the upper layers of all inlets and in the coastal waters, this being detectable down to about 40 meters, or exceptionally to 100 meters. None of the inlets contained stagnant bottom water, although all but one were much deeper inside than at the "threshold". Comparison of 1926 and 1949 observations in similar adjacent inlets gives no indication of warming of the bottom waters over that period.

INTRODUCTION

The *Blue Dolphin* during the three summers (1949–1951) carried out oceanographic survey operations in Labrador coastal waters.[2] The coastal waters of Labrador may be considered part of "Eastern Arctic Waters", which have been defined by Dunbar (1951) as being bounded on the north by the Lincoln Sea, on the south by the Strait of Belle Isle, on the east by Cape Farewell, and on the west by the western shore of Hudson Bay.

Within the Eastern Arctic waters there is a series of counterclockwise circulation in Baffin Bay, Hudson Bay, Ungava Bay, and the Labrador Sea, all of which are in turn a part of the larger circulation formed by the North Atlantic Drift and the waters of the Arctic Ocean (Figure 1).

The coastal waters of Labrador on the southern margin of this region are under the influence of the Labrador Current, the coastal drainage, and (in the Strait of Belle Isle) Gulf of St. Lawrence water. The predominant influence is the Labrador Current which, flowing south along the the coast of Labrador and Newfoundland to the Grand Banks, represents the most southerly extension in the Atlantic of water of Arctic origin. For nearly six months of the year the Labrador Current brings southward pack ice which blocks the entire coast and extends south to the Newfoundland shores in March and April to provide whelping grounds and the site of the great western Atlantic seal fishery. During the

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summer months the pack ice departs, land drainage reaches its maximum and Labrador coastal waters become the site of a great cod fishery.

Earlier work has defined the Labrador Current, but the extent of our knowledge of the immediate coastal waters is restricted to the observations of temperature and salinity made in Nachvak Fjord by the Brown Harvard Expedition of 1900 and to the work of Iselin in the *Chance* in 1926. The former data have apparently never been published except for the single subsurface temperature reading of 29°F. recorded in the general account of Delabarre (1902). In addition to the two sections across the Labrador Current off Sandwich Bay and off Nachvak Fjord, observations from the *Chance* included, in the immediate coastal waters, three stations in Nachvak Fjord, one in Saglek Bay, and one in Ekortiarsuk Fjord (Iselin, 1932).

FIGURE 1. (After Dunbar, 1951.)

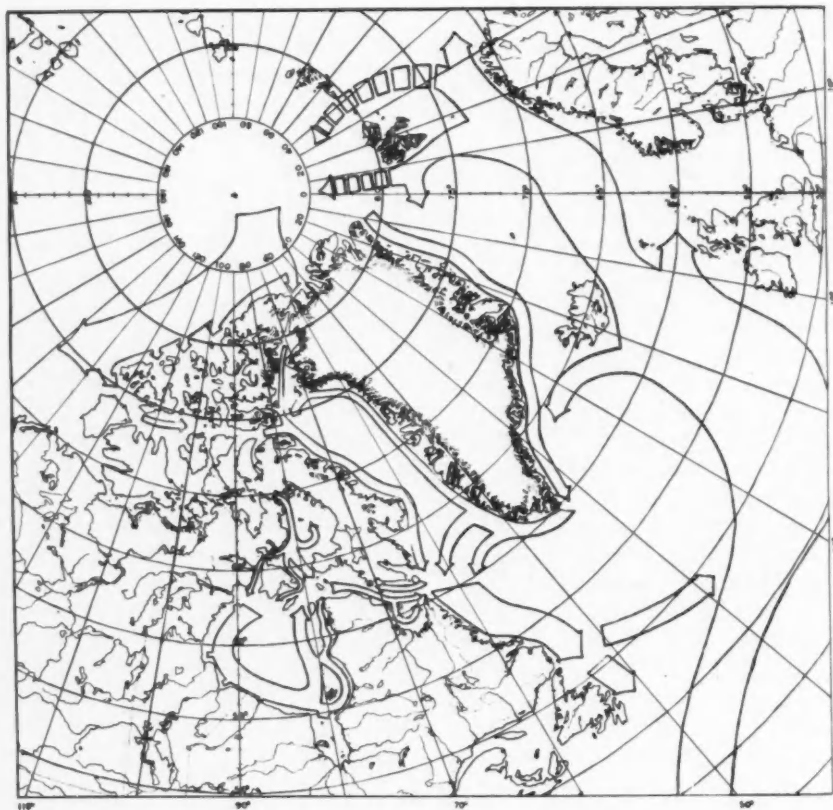The program of work undertaken by the *Blue Dolphin* centered about a more complete and detailed study of the fjords, inlets, and immediate coastal waters. Examination was made of St. Lewis Inlet, Kaipokok Inlet, the Nain area, Hebron Fjord, and Seven Islands Bay; while a detailed study was undertaken in the Hamilton Inlet–Lake Melville estuary (Figure 2). These oceanographic studies
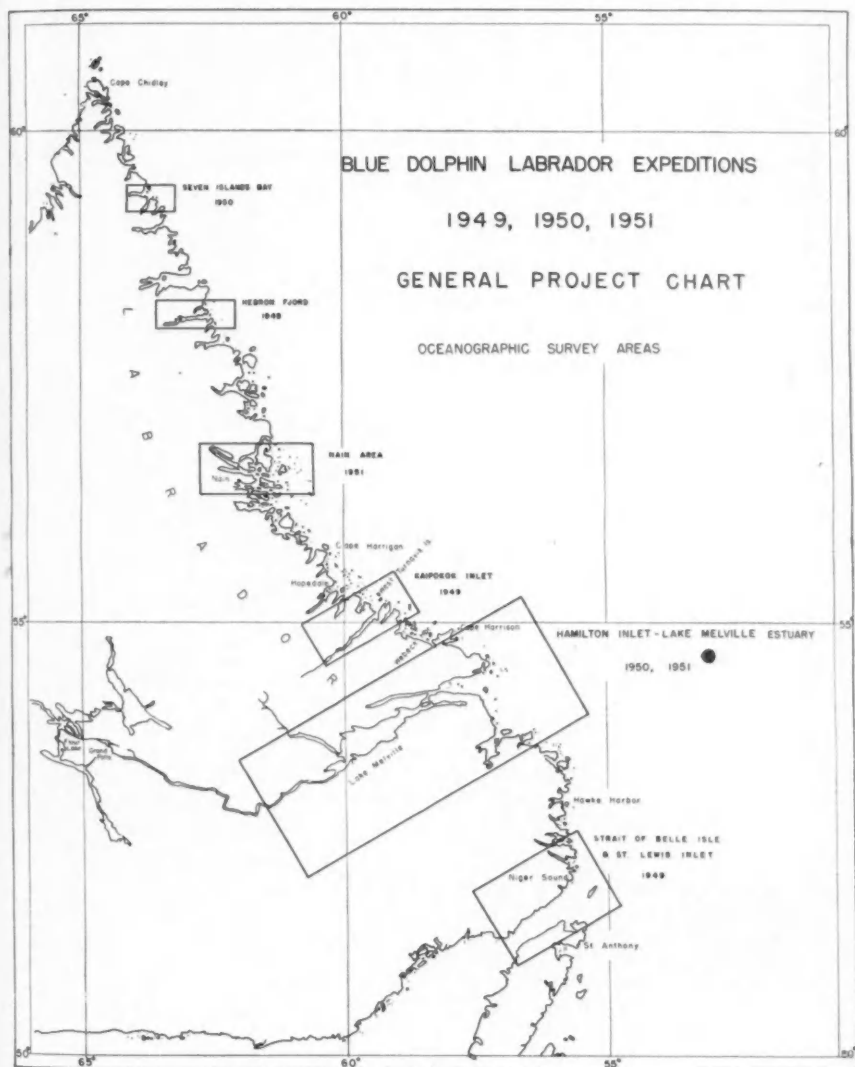

FIGURE 2

involved surface and subsurface measurements of temperature, salinity, dissolved oxygen content, and at certain stations inorganic phosphate determinations. In addition, tidal, current, and river-volume measurements were made in the Hamilton Inlet–Lake Melville estuary. Stations were occupied from the coastal waters along shore to the inner reaches of the inlets and fjords. At many of these stations and all along the coast, biological collections were made which included surface and subsurface plankton hauls, benthonic collections by means of dredge and trawl, and intertidal and fresh-water collections.

Many of the bays and inlets along the Labrador coast are of the fjord type of configuration with a threshold across the entrance and a deeper inner part, although these are nowhere as deep and spectacular as the more classical fjords of Greenland. The deepest fjord examined by the *Blue Dolphin* was Hebron Fjord where a depth of 255 meters was obtained. St. Lewis Inlet was the only embayment examined without a well-defined threshold. Except in the case of the Hamilton Inlet–Lake Melville area the lack of sufficiently detailed soundings prohibits precise determination of the actual threshold depths. The threshold and inner depths of the areas examined are taken in part from existing soundings and in part from surveys made by the *Blue Dolphin* with a recording fathometer (Table I).

TABLE I. Threshold and inner depths of six Labrador inlets

	Threshold depth	Inner depth
	meters	*meters*
St. Lewis Inlet	None	50
Lake Melville	29	220
Kaipokok Inlet	34	130
Nain Bay Area	25	110–80 (inner bay)
Hebron Fjord	55	255
Kangalaksiorvik Fjord (Seven Islands Bay)	27	105

EXCHANGE OF WATER BETWEEN INLETS AND OCEAN

Aside from the practical importance to economic biology, the main interest in fjord studies is in determining to what extent the water within the fjord is influenced by the water outside the fjord, and what exchange relationships exist. In the cases of certain Norwegian fjords with very shallow thresholds, isolation and stagnation of the bottom water takes place with the depletion of oxygen and the production of hydrogen sulphide (Strøm, 1936). These fjords are in some cases periodically ventilated and the bottom water is renewed; in other cases this happens rarely or not at all.

The Labrador Current, which is the dominant water along the Labrador coast, has been divided into two bands (Smith, Soule & Mosby, 1937). The inner shelf band, comprising about two-fifths of the total volume, is largely composed of true Arctic water from Baffin Bay and Hudson Strait; while the outer or

slope band is largely contributed by the West Greenland Current and is of higher temperature and salinity.

The temperature-salinity relationships established by the *Blue Dolphin* for Labrador inlets and fjords during the summer regime (July to August 1949–1951) are shown in Figures 3 and 4, together with the Labrador Current polygon (after Dunbar, 1951). Observations included are from depths close to or greater than 50 meters.

In uncomplicated fjords, with or without a threshold, the bottom water (generally below 50 meters) may be clearly identified as Labrador Current water of Arctic origin in accordance with the temperature-salinity relationships set forth by Dunbar. In topographically complicated areas special conditions of dilution and warming occur. Such are the Hamilton Inlet–Lake Melville estuary, where the inner body of water, Lake Melville, is separated from Hamilton Inlet and the ocean by both a constriction and a sill, and the Nain area where the inner bay itself is separated from the sea by some twenty miles of broken runs through a maze of islands.

No West Greenland influence was noted in the inlets. In all cases the tendency is towards warming and freshening rather than warming and salting.

The fact that certain observations fall below the Labrador Current polygon with respect to temperature may be explained by a probable lag in the exchange of fjord water. These summer observations of the bottom water likely reflect con-

FIGURE 3

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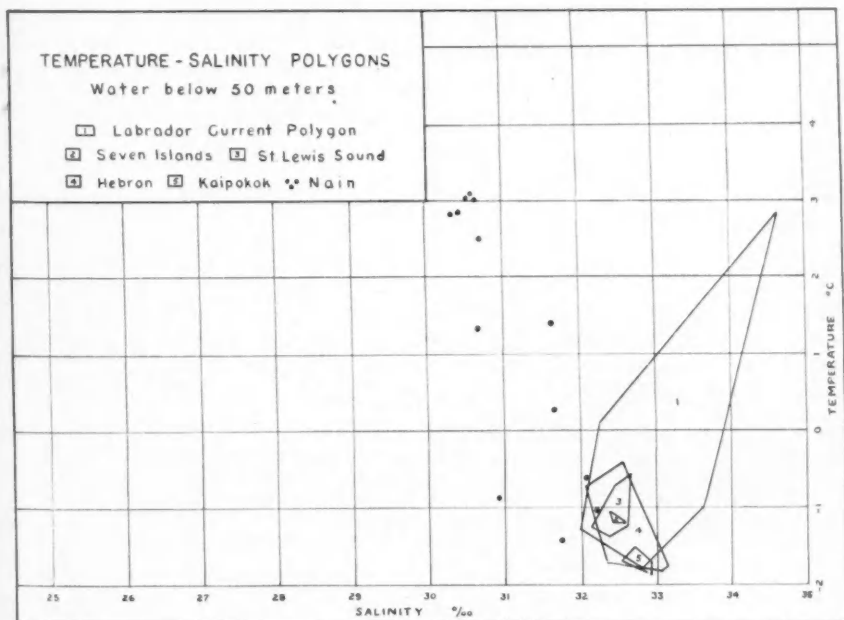
ditions of an earlier season, possibly a winter turnover. The observations from which Dunbar's relationships are established were taken only from the latter part of July through September.

The observations from Nain form such an irregular pattern that the individual observations are shown rather than a polygon. The two more typical Labrador Current observations are from the coastal fringe; the group of warm, lower salinity observations come from the vicinity of Nain and Strathcona Run, while in the inner reaches of Nain Bay itself cold but slightly freshened water occurs. This would indicate a relatively strong but irregular pattern of summer warming, likely influenced by the complicated topography of the various runs. As with the other inlets, there seems to be an isolation of the cold bottom water (though slightly freshened) in the inner part of the bay itself.

In the Hamilton Inlet–Lake Melville estuary, where more detailed investigations have been carried out over a period of two years, a clearer pattern of the conditions can be seen. In Figure 4 observations indicated by polygons are shown for Hamilton Inlet in July 1950, July 1951, and August 1951 together with corresponding polygons for Lake Melville.

In July 1950 typical Labrador Current water was present in Hamilton Inlet while in July 1951 water both fresher and slightly warmer was observed. This seems to be directly reflected in a corresponding change within the lake and supports the conclusion drawn from the study of the circulation and exchange
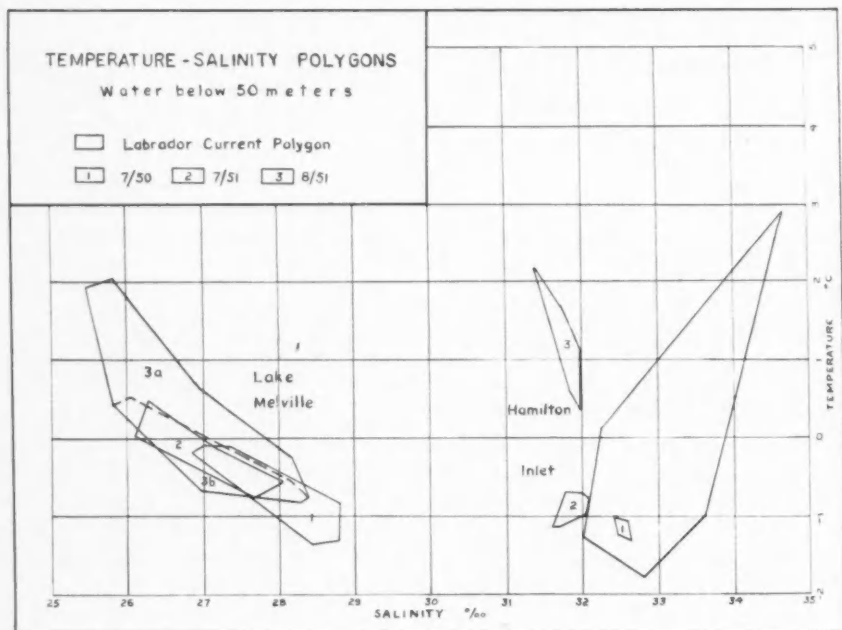
FIGURE 4

within the estuary that the Hamilton Inlet water is the principal source water for Lake Melville. The exchange mechanism through the constriction and over the sill at the Narrows is highly complicated, but the net result is the dilution of the source water by about five parts per thousand, referring to water at 50 meters and below.

The picture of thermal exchange is different. The summer warming of Hamilton Inlet is reflected only in the very eastern end of Lake Melville. The upper part of the August 1951 polygon represents the observations made in the vicinity of Gull Island, ten miles within the lake, while the lower half represents observations from the main body of the lake.

A flushing time of 170 days or approximately six months has been computed for Lake Melville by Backus (1952) using the formula:

$$\text{Flushing time} = \frac{\text{Total accumulated fresh water}}{\text{River flow}}$$

Although this computation is subject to some error, owing to the long period involved and to the likelihood of incomplete vertical mixing, it does give an idea of the magnitude of the flushing action. We may conclude that during a year the water within Lake Melville is completely renewed between one and two times.

Thus, during the short summer season complete reflection of any warming of the Labrador Current and of Hamilton Inlet water will in general not be shown in Lake Melville; and, except in the easternmost end of the lake, the temperature below 50 meters will not rise appreciably. Relative stability of the main mass of water is thus indicated.

However, during the annual cycle with at least one complete flushing of the lake, a reflection of any longer-term changes in the Labrador Current and Hamilton Inlet will be reflected in the bottom water of Lake Melville, as is shown by comparing the July 1950 and July 1951 observations.

The uniformly high oxygen content observed at practically all stations both in the Hamilton Inlet–Lake Melville estuary and in all the fjords and inlets studied, precludes any possible stagnation such as may occur in the Norwegian fjords. However, the very cold bottom water of −1.8°C. in Kaipokok Inlet and Hebron Fjord during July and August, when a certain amount of warming of the water immediately along the coast takes place, indicates a lag in the exchange of water. It is unlikely that even during September, when the Labrador Current and the coastal water have reached their greatest warming, the temperature rises appreciably in the bottom water of these fjords. The summer conditions with a sharp warming and freshening of the surface layers produces an unfavorable density gradient for vertical movements of water, and the bottom water is isolated during this season. Conditions for exchange and renewal of the bottom water due to vertical instability must be supposed more favorable during the winter months.

Although the seasonal warming does not affect the bottom water within the inlets and fjords, surface warming occurs with temperatures as high as 10°C. In Lake Melville, with the greater heat of the interior, temperatures as high as 18°C. have been recorded. Significant warming occurs to considerable depths in various

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localities along the immediate coastal fringe. This was particularly noted off Nain where, at 100 meters and at 70 meters, temperatures of 2.52° and 3.02°C. respectively were recorded. Bathythermograph observations showed such warming to occur elsewhere in an irregular pattern to the south of Nain. In Hamilton Inlet during July 1950 and July 1951, temperatures less than −1°C. were obtained, whereas in August of both 1949 and 1951 temperatures above 1°C. were observed at corresponding depths. This warming may vary in degree and extent from year to year, but very definitely occurs.

. Year-around observations of the Labrador Current are lacking, so that the seasonal picture cannot be determined. Surface warming occurs during the summer and is relatively constant from year to year (Smith *et al.*, 1937); but the core of the inner band of cold water remains cold and would seem to form a more-or-less permanent barrier along the shelf with little seasonal variation. A *Blue Dolphin* section from the Camp Islands to Belle Isle on 28 August 1949 showed water of −1.3°C. at 100 meters. This is in agreement with observations of the 1923 Expedition by the Biological Board of Canada to the Strait of Belle Isle which show on 18 August −1.6°C. at 100 meters just to the north of Belle Isle, and −1.0°C. at 100 meters within the Strait itself (Bailey & Hachey, 1951a).

SUMMARY AND DISCUSSION

In summary it can be stated that in the lower levels, below 40–50 meters, in all the Labrador fjords and inlets examined, temperatures of less than 0°C. prevail at all times, providing a high-arctic marine environment as defined by Nybelin (1949). Although the results of winter observations are not at this time available, this environment may be postulated also for all levels during the winter season. During the summer, however, owing to the warm land drainage and the warming of the Current and coastal waters, a break in these conditions occurs in the layers above 40 meters and to greater depths in certain localities along the coastal fringe.

The marine life in Labrador coastal waters must be fitted to this physical environment. As might be expected, many high-arctic circumpolar forms are present, such as, to mention a few at random from the fishes: *Boreogadus saida*, the polar cod; *Salvelinus alpinus*, the arctic char; *Lumpenus medius*, a snake blenny; *Lycodes turneri*, an eel-pout; *Aspidophoroides olriki*, an agonid fish; and *Gymnelis viridis*, a zoarcid fish.

The geographical location of Labrador at the southern limit of the Arctic marine environment with a seasonal amelioration renders penetration possible by certain forms with boreal affinity. Examples of such organisms among the fishes are *Gadus callarias*, the cod; *Pholis gunnellus*, the rock-eel; *Cyclopterus lumpus*, the lump fish; *Salmo salar*, the salmon. Among the invertebrates *Balanus hameri*, a barnacle, serves as an example.

Finally we have great interest in what the long-range environmental trends may be. It is well known that considerable amelioration in climate and in marine environment has occurred throughout the north polar regions, particularly in West Greenland, where these changes have had a profound effect on the entire

economy of the country by permitting the establishment of an important cod fishery (Jensen, 1939). West Greenland observations, though taken at variously irregular intervals, do permit establishment of certain long-term trends in the hydrographic conditions. It is apparent that a warm period with greater Atlantic influence was in progress from 1880 to 1895 and was followed by a cold period from 1900 to 1926. At this time the present warm period began and has continued to date with a possible maximum in the middle 1930's. No definite answer is now available as to whether the present warm period is drawing to a close or not (Dunbar, 1951).

In the Canadian Arctic any warming or Atlantic influence would of necessity be of far less amplitude than in West Greenland and the paucity of observations during the past fifty years render any competent analysis difficult. Bailey and Hachey (1951b) compare the 1930 *Loubyrne* observations with the 1948 *Haida* observations to show an increasing Atlantic influence in Hudson Bay.

Evidence from Labrador coastal waters is limited to comparison of the 1926 observations of the *Chance* in Nachvak Fjord, with the 1949 observations of the *Blue Dolphin* in Hebron Fjord, which fjords are similar in structure and within 50 miles of each other (Table II).

TABLE II. Comparison of Nachvak and Hebron Fjords, from the observations of the *Chance* in 1926 and the *Blue Dolphin* in 1949.

Depth	Nachvak, 1926		Hebron, 1949	
	T°C.	Sal. ‰	T°C.	Sal. ‰
0	+4.1	—	+6.4	26.34
10	−0.3	31.52	+0.91	31.27
20	−0.21	31.76	—	31.67
30	. —	—	−0.53	32.01
50	−0.02	32.02	—	—
60	—	—	−1.31	32.54
100	−1.83	33.12	−1.73	33.00
200	−1.8	33.20	−1.81	33.06

A striking similarity between conditions of 1926 and 1949 is at once apparent. Some small variation can be noted in the upper layers; but the fjord bottom water, which would reflect any long-term changes in the Labrador Current, is strikingly similar and certainly in no case shows increased Atlantic influence. Indications are therefore that the Labrador Current maintains an effective barrier along the continental shelf and that the amelioration of hydrographic conditions, as noted since the 1920's in West Greenland, has not been reflected in the coastal waters of Labrador. This difference from the conclusion of Bailey and Hachey regarding Hudson Bay (1951) sets forth clearly the necessity for continued and repeated studies of Eastern Arctic waters.

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Seasonal Fluctuations in the Selected Temperature of Speckled Trout, Salvelinus fontinalis (Mitchill)

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ABSTRACT

The selected temperature of two- to three-inch trout (*Salvelinus fontinalis*, Mitchill) was determined in a horizontal gradient a number of times during the months of November, December, January, February and March. The data, which were collected over four years, indicated that during the early part of winter (November, December and January), there was a fall of the selected temperature which paralleled in a general way a gradual fall of the acclimation temperature. The consistency of this parallelism was so poor, however, as to suggest that at least part of the change in selected temperature was relatively independent of the change in acclimation temperature. During the later part of the winter (February and March) there was a rise of the selected temperature which occurred regularly, regardless of whether the acclimation temperature rose, fell or remained constant. It is concluded that there was, for these animals, a seasonal change of the selected temperature which was distinct from the changes in selected temperature brought about by changes of the acclimation temperature.

INTRODUCTION

FISH which are free to move about in a gradient of temperature are usually found to be confined to only a small portion of the total range of temperatures available to them. This behaviour is common to many kinds of animals and here will be called temperature "selection"[2] .

The actual temperatures selected by organisms belonging to closely related groups may vary considerably. Thus Herter (1924, 1934), Nieschulz (1933, 1935), Bodenheimer (1930a), Bodenheimer and Klein (1930) and Gunn (1935) have all shown that for insects the selected temperature differs from genera to genera and from species to species. Wilkes (1941–42) was able to separate one strain of Chalcid from another on the basis of a difference in the temperature selected by each. Herter (1940–41) demonstrated differences in selected temperature among adult lizards of various genera and species and the experiments reported by Herter (1934, 1935, 1936), Herter and Sgonina (1938–39) and Bodenheimer (1941) indicate similar differences among rodents. Herter (1935, 1936), claims that the selected temperatures of mice are sufficiently characteristic to serve as criteria for species and even race distinctions.

Although there are very few data for fish as yet, comparable differences undoubtedly exist among them (Jackson, Price, Berst and Lapworth, personally communicated; Fisher and Elson, 1950). Care must be taken, however, in making

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[2]This name is a convenient one provided that the term selection is understood to be an objective description of what the animals are observed to do, that is, to signify only that the organisms spend more time in one special region than in others; and provided that the common conception of "selection" as an act involving will is avoided.

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comparisons of the selected temperatures of different animals, for individuals of the same species do not necessarily select the same temperature in gradients: the selected temperature has been observed to change with the previous temperature history (that is, the acclimation temperature) of the individuals in some insects (Bodenheimer and Schenkin, 1928; Henschel, 1929; Herter, 1924, 1934; Homp, 1938), but not in others (Bodenheimer and Klein, 1930). It is similarly changed in frog tadpoles (Scott and Fisher, unpub.), in fish (Doudoroff, 1938; Fry, 1947) and in mice (Herter, 1934; Herter and Sgonina, 1938–39). In some animals selection appears to vary with the stage of development, for Bodenheimer (1930b) found that individuals of each of the different instars of the desert locust have different and characteristic selected temperatures, Thomsen and Thomsen (1937) found that the selected temperature of housefly larvae shifts regularly with age of the larvae, and Herter (1935, 1940–41) recorded differences in the temperatures selected by young and old mice and young and old lizards respectively.

One must conclude from these investigations that the temperature selected by an organism, while characteristic of it to a degree, is capable of considerable modification as the physiological state of the organism changes.

Seasonal changes in physiological characteristics are known to occur in many animals. In poikilotherms such changes are often believed to be brought about by regular fluctuations in the environmental temperature or light. In some fish, however, there is evidence that certain seasonal physiological changes are not directly dependent on changes in temperature. Thus a rise in the rate of oxygen consumption by Pacific killifish occurs in the spring independently of environmental temperature fluctuations (Wells, 1935). Similarly, changes which are apparently independent of variations in acclimation temperature take place in the growth rate of trout (Brown, 1946), and in the blood-cell count of the pumpkinseed fish (Schaefer, 1924–25) during the early spring and in the late autumn.

The importance of light in determining the time of sexual maturation has been demonstrated by Hoover and Hubbard (1937) and by Bullough (1939) who showed that trout and minnows respectively could be induced to mature sexually, in advance of their natural breeding seasons, by artificially controlling light and temperature fluctuations. Bullough (1940) further found, however, that in minnows kept in total darkness or exposed to a very limited period of light each day, sexual maturation was delayed but not prevented. Bullough concluded that there is, in these fish, an inherent reproductive rhythm which is independent of external factors but which is "reinforced and rendered more precise in its time of action by the effects of the seasonal variations of the external environment". Brown's (1946) work is further indication of the inherent nature of some physiological rhythms, for her experiments show that seasonal fluctuations in growth rate of brown trout occur in conditions of constant light and temperature.

It seemed possible that the selected temperature too might undergo changes with the seasons that were independent of the concomitant changes in the temperature to which the organisms were exposed. We have, therefore, assembled a number of determinations of the temperature selected by speckled trout, in order

to permit an examination of them for any seasonal trends. They were collected over a period of four years, incidental to various investigations of other aspects of temperature selection which were being undertaken in this laboratory. Since these observations were not made at regular intervals throughout the year, the data available are incomplete. They show beyond reasonable doubt, however, that the temperature selected changes in the early spring even though the acclimation temperature remains constant, and they indicate a similarly independent change in the late autumn.

MATERIALS AND METHOD

The trout (*Salvelinus fontinalis* Mitchill) used in these experiments were between two and three inches long. They were obtained from private or government hatcheries and were held in running Toronto tap water. They were fed beef liver regularly.

The temperature of the tap water from which the fish were taken for an experiment was recorded as a regular formality each time a selection experiment was done. All experimental animals were exposed to the normal diurnal light conditions.

The selected temperatures were determined in a horizontal temperature gradient which was set up in a trough five feet long and two inches wide. This trough had glass sides and a one-quarter-inch-thick copper bottom. The latter was coated with water-resistant varnish to prevent copper ions from affecting the fish. A small steady flow of water was maintained through the trough, water entering at one end at a temperature of 1–2°C., after passing over ice. The water was removed at the other end by a siphon, an adjustment of which permitted any desired depth to be maintained. In practice the depth was sufficient to allow the experimental animals to swim clear of the bottom but not sufficient to permit much vertical movement. It was established in preliminary trials that the flow was not rapid enough to influence the distribution of the fish in the trough. As it moved along the trough, the water was warmed by a series of electric heaters beneath the copper bottom. These heaters were independently controlled by means of rheostats. Gradients extending from 1° to 21° or 24°C. were employed.

The trough was illuminated from above by the diffuse reflection from the surface of buff-coloured cardboard which extended the length of the trough. Light reached the cardboard reflector from six 110-volt incandescent lamp bulbs which were located approximately 12 inches away from the cardboard and were evenly spaced along it. The bulbs employed were 7½- or 25-watt, usually the former. In this range of intensity at least, as will be shown elsewhere, the temperature selected is independent of the light intensity. The trough and lighting fixtures were enclosed except for a narrow slit along the trough through which the organisms were observed. The experiments were done in a well-darkened room.

As a general routine the gradient was first established and then five fish were placed in the trough. Thereafter the positions in the trough of each of the five were noted every two minutes during an observation period of one and one-half

hours, and were recorded on one-millimeter graph paper ruled to correspond to one-inch intervals marked on the trough. Gradient temperatures were entered on the same sheet every 15 minutes, the temperatures being measured at 5-inch intervals along the trough by means of thermocouple and galvanometer.

In analysing the records, the number of occasions upon which animals were found in each 3-degree interval of temperature was counted for the whole observational period. A histogram showing the average distribution of the organisms in the gradient was then constructed.

<div align="center">RESULTS</div>

A typical histogram illustrating the distribution of trout in a gradient of temperature is given in Figure 1. This particular experiment was done toward the end of March when the temperature of the tap water in which the fish were living was 4.0°C. It is evident that these organisms were most commonly observed in the temperature interval 9–12°C.; this, then, being the selected region. The modes of such histograms are taken as the selected temperatures in accordance with common practice. They were calculated using the method outlined by Arkin and Colton (1935, pp. 23–24).
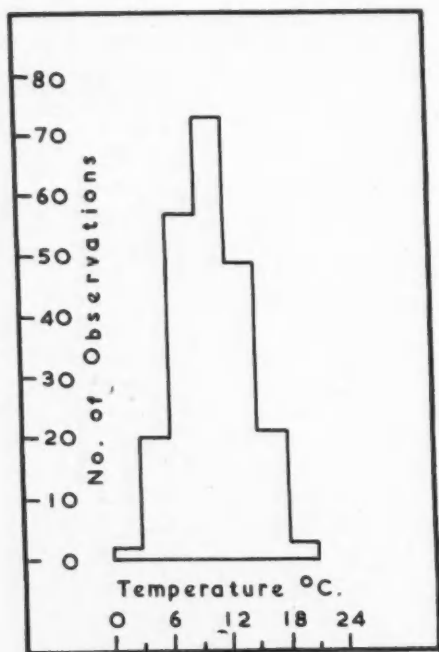

FIGURE 1. The frequency with which individuals of *Salvelinus fontinalis* were observed in different regions of temperature in a temperature gradient.

The data available involve five different stocks of fish and were collected over four successive winters. The 82 determinations of the selected temperature were made at intervals extending from the middle of November to the end of March. To facilitate examination of them in relation to the time of year, and the temperature at which the various groups of organisms used were living, the data for each year will be considered separately. Those for early winter will be found in Figure 2, A, B, and C, the dots in each case representing the selected temperature
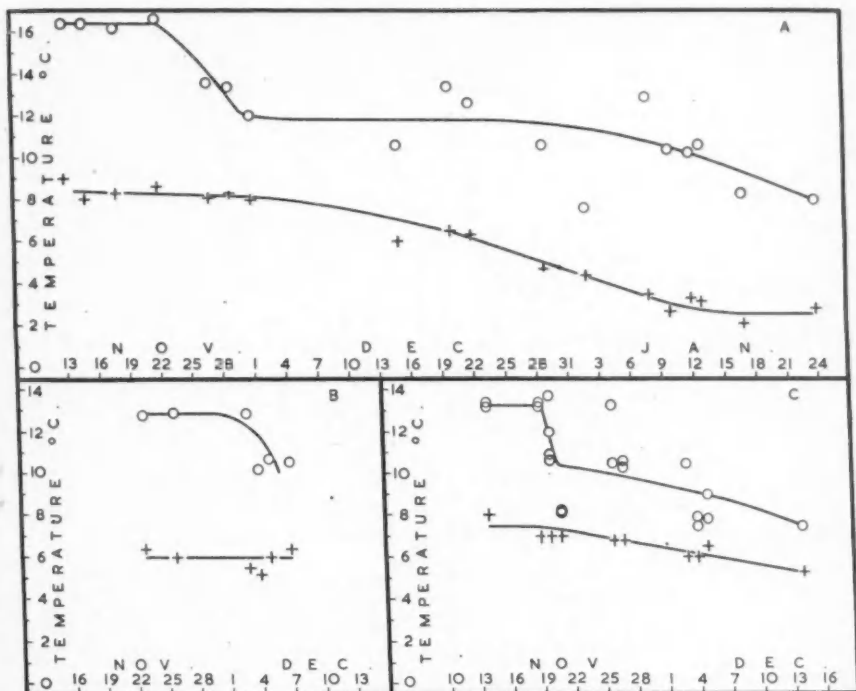

FIGURE 2. The temperature selected by *Salvelinus fontinalis* (circles) and the temperature to which the fish were acclimated (crosses), respectively, from November to January of several years.

and the crosses the temperature of the water in the laboratory rearing tanks from which the animals were taken. The latter temperature (crosses), which was the temperature to which the fish were acclimating, fell gradually throughout the period illustrated in Figure 2. Since selected temperatures vary with the temperature to which fish are acclimated (Doudoroff, 1938; Fry, 1947), it would be expected that the temperature selected would likewise be found to change throughout this period. Actually, as the figure shows, the selected temperature did fall in accordance with the expectation. In Figures 2A and 2C the fall was initially pre-

cipitous and then more gradual. The interval of time covered by the observations in Figure 2B, however, appears to include only the initial rapid drop.

As has already been indicated, each point in Figure 2 was the temperature selected by a group of five fish taken from the laboratory stock. Undoubtedly individual fish vary in respect to the speed with which they acclimate as well as the degree to which they do. It was therefore remotely possible that the rapidity indicated for the initial drop was an artifact resulting from the particular groups of fish taken for the succession of experiments. As it happened, however, there were five cases in which an individual group of fish in the course of successive experiments showed the relatively sudden drop of the selected temperature. It seemed, therefore, that the precipitous fall of the selected temperature which occurred, according to Figure 2, about the first of December must be thought of, not as an artifact arising from the use of particular groups of fish, but as a phenomenon characteristic of each animal.

Attention was drawn above to the fact that a decrease of the selected temperature would have been expected in early winter by virtue of the drop in acclimation temperature. However, it is difficult to believe that all of the decrease which was actually observed could have been due to the change in the acclimation temperature, for in one instance (Figure 2A) it is quite clear that the rapid change of the selected temperature, a drop from 16.5° to 12.5°C. took place, while the temperature of the rearing tanks was essentially constant. Moreover, the rate at which the acclimation temperature was falling in Figures 2A and 2C was so slow that it seems somewhat unreasonable to associate the rapid drop in the selected temperature with the decline of the acclimation temperature even in these two cases. Perhaps, then, there is some other explanation of the initial *rapid* fall. The *slow* decrease of the selected temperature which continued throughout December and January (Figures 2A and 2C) undoubtedly represented the change brought about by the fall of the acclimation temperature.

The data obtained during February and March for four separate years are given in Figure 3. Each year the selected temperature began to rise in March. In two of the years (Figures 3B and 3C) the temperature of the rearing tanks had also begun to rise at this time. In one of the other two years (Figure 3D) the acclimation temperature was constant throughout this period and in the other (Figure 3A) it actually fell during this period. Considering the data for all four years, then, it can be seen that whether the acclimation temperature rose, remained constant or actually fell, the selected temperature rose. Quite evidently it would be incorrect to associate, necessarily, the rise in the selected temperature in March with a rise in the acclimation temperature. Undoubtedly, during the spring there is a rise in the selected temperature due to a rise in the acclimation temperature, but the change in selected temperature to which attention is drawn here does not appear to be *that* rise.

It is now clear that neither the rapid fall of the selected temperature which occurred in early winter nor the rise which occurred in early spring is satisfactorily accounted for solely on the basis of a change in the acclimation temperature. It appears that there was a change in the selected temperature about

December 1 and again in March which was independent of any change in ac-
climation temperature. These changes must be thought of, it seems, as physio-
logical ones which were related to the seasons as the sexual cycle is; and which
were independent, relatively at least, of the changes in selected temperature
brought about concomitantly or subsequently by changes in the acclimation
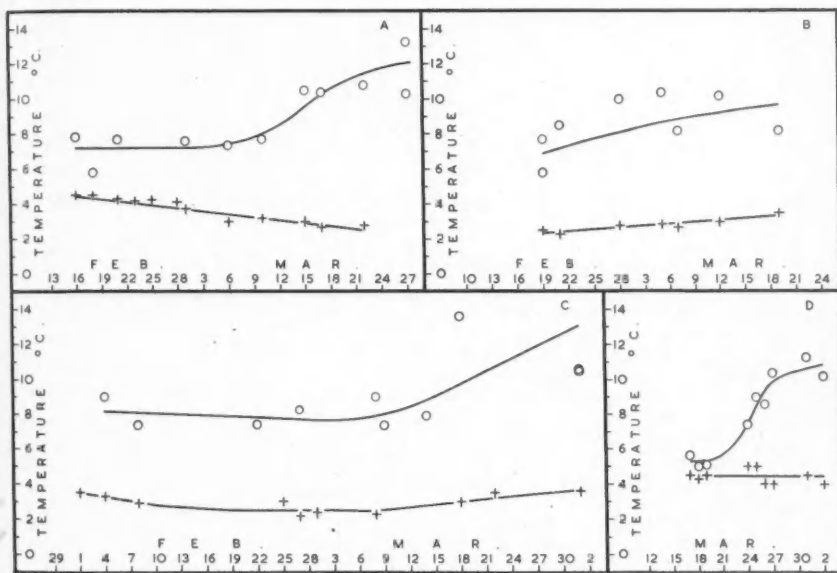temperatures.

FIGURE 3. The temperature selected by *Salvelinus fontinalis* (circles) and the temperature
to which the fish were acclimated (crosses) through February and March of several years.

SUMMARY AND CONCLUSIONS

1. The temperature selected by speckled trout in a horizontal temperature
gradient was determined at intervals from November to March.

2. The selected temperature fell through November, December and January
from something over 12°C. to about 8°C. This drop accompanied a fall in the
temperature of the tap water in which the organisms were maintained during the
experiments. The relation between the selected temperature and the tap-water
temperature was not at all well defined, however.

3. The data suggest that about December 1 the selected temperature
dropped quite rapidly by several degrees, independently of the decline of the
tap-water temperature.

4. The selected temperature rose during February and March independently
of any change in tap-water temperature.

5. It is suggested that these changes in selected temperature—the sudden drop in early winter and the rise in early spring—were seasonal ones, independent in the first instance of acclimation temperature.

ACKNOWLEDGEMENTS

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Upper Lethal Temperatures
of Some British Columbia Freshwater Fishes[1]

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(*Received for publication June 28, 1952*)

ABSTRACT

During the summers of 1950 and 1951 the upper lethal temperature was measured for 14 species of freshwater fishes, representing five families. The fish were captured from lakes in the southern Okanagan Valley, and the experiments were conducted in the Summerland Trout Hatchery, Summerland, B.C. The upper temperature (°C.) at which 50 per cent of the fish died in 24 hours was estimated as follows, the approximate acclimation temperature being given in brackets: *Salmo gairdneri kamloops* fingerlings, 24.0(11); *Oncorhynchus nerka kennerlyi* fry, 22(11); *Catostomus catostomus*, 27(11.5), 26.6(14); *Mylocheilus caurinus*, 27(10), 27.1(14); *Rhinichthys falcatus*, 28.3(14); *Richardsonius balteatus*, 25(9–11), 27.6(14); *Cottus asper*, 24.1(18–19); *Catostomus macrocheilus*, 29.4(19); *Micropterus salmoides*, 28.9(20–21); *Ptychocheilus oregonensis*, 29.3(19–22); *Ameiurus melas melas*, 35.0(23); *Perca flavescens*, 26.5(18), 29.2(22–24); *Lepomis gibbosus*, 28.0(18), 30.2(24); *Cyprinus carpio*, 31–34(20), 35.7(26).

INTRODUCTION

During the summer of 1950, preliminary observations were carried out on the upper lethal temperatures of five species of fishes found in Okanagan lakes (Black and Black, 1950). A correlation between the order for lethal temperatures and the carbon dioxide asphyxiation curves was noted for four of the five species. These findings prompted the extension of the investigation during the summer of 1951.

In this paper, use of the term acclimation is restricted to the exposure of an organism to temperature conditions in a laboratory, whereas the term acclimatization refers to temperature changes that are imposed by the natural habitat.

As shown by a number of workers, the upper lethal temperature relationships afford a valid clue to the abilities of and limits for fishes to tolerate environmental changes in temperature (Hathaway, 1927; Fry *et al.*, 1942, 1946; Brett, 1941, 1944, 1951; Hart, 1947, 1952). The shift in lethal temperatures with acclimation to temperature was also measured by these workers.

No direct information was gained on the interesting problem of the mechanism of thermal death in fishes. Discussions of this fundamental question will be found in the writings of Huntsman (1924), Huntsman and Sparks (1924), Battle (1926), Cameron (1930), Belehradek (1935), Heilbrunn (1943), Fry (1947), Prosser *et al.* (1950), and Hoar and Cottle (1952).

MATERIAL AND METHODS

Thirteen species of freshwater fishes of the Okanagan area were investigated during May, June and July, 1951. The common and scientific names, total numbers

[1]Contribution from the Department of Physiology, Faculty of Medicine, University of British Columbia, and from the British Columbia Game Department, both at Vancouver, B.C.

used, number used per test, weight average and range, place of capture and temperature of surface water, and duration of exposure of captured fish at 11°C. are given in Table I. The fishes were identified according to the key provided by Carl and Clemens (1948), and the identification of the fine-scaled sucker, chub, silvery-grey minnow and northern black catfish was checked by Dr. W. A. Clemens. Mr. T. Northcote confirmed the identification of the prickly sculpin.

TABLE I. Common and scientific names, total number used, usual number used for test, weight (average and range), place of capture and temperature of surface water, and duration of exposure of captured fish at 11° C., for species studied at Summerland, B.C., May-July, 1951.

Species	Total No. of fish used	Usual No. used per test	Weight (average and range)	Place of capture	Temperature of water at place of capture	Duration of exposure to 11° after capture (days)
			g.		° C.	
Kamloops trout (fingerling)	40	10	26.1	Summerland	11.0°	Hatched and
Salmo gairdneri kamloops			14.0–54.2	trout hatchery		reared at 11°
Fine-scaled sucker	36	6	44.3	Garnet	14.4°	8–22 days
Catostomus catostomus			32.8–60.8	valley dam		
Coarse-scaled sucker	60	10	19.4	Okanagan Lake	18.9°	2–10
Catostomus macrocheilus			2.0–48.5	at Summerland		
Carp (Lot 1)	70	10	12.8	Twin Lakes	20.0°	4–15
Cyprinus carpio			5.3–32.7			
Carp (Lot 2)	40	10	28.2	Twin Lakes	25.6°	1
			6.9–64.6			
Chub	60	10	9.4	Okanagan Lake	14.4°	5–8
Mylocheilus caurinus			5.9–26.0	at Summerland		
Silver-grey minnow	68	10	3.3	Garnet	14.4°	5–8
Rhinichthys falcatus			1.1– 7.4	valley dam		
Squawfish	56	10	8.9	Okanagan Lake	18.9° to	4–7
Ptychocheilus oregonensis			0.7–71.1	at Summerland	22.2°	
Redside shiner	51	10	6.3	Garnet	14.4°	6–12
Richardsonius balteatus			2.1–10.5	valley dam		
Northern black catfish	50	10	51.9	Osoyoos	23.3°	4–6
Ameiurus melas melas			9.7–138.	Lake		
Yellow perch (Lot 1)	36	6	9.8	E. Smith's pond	17.8°	26–32
Perca flavescens			2.0–24.8	near Oliver, B.C.		
Yellow perch (Lot 2)	70	10	8.6	E. Smith's pond	22.2°–24.4°	5–11
			2.9–50.5	near Oliver, B.C.		
Largemouth bass	28	6	52.2	Shannon	20.0°–21.1°	4–20
Micropterus salmoides			5.1–127.	Lake		
Pumpkinseed (Lot 1)	18	6	19.3	E. Smith's pond	17.8°	28–34
Lepomis gibbosus			3.6–44.0	near Oliver, B.C.		
Pumpkinseed (Lot 2)	60	10	15.9	E. Smith's pond	22.2°–24.4°	5–10
			1.7–42.7	near Oliver, B.C.		
Prickly sculpin	61	10	4.0	Okanagan Lake	18.3°–18.9°	9–23
Cottus asper			0.6–24.3	at Summerland		

Not all the fishes studied are native. The following are believed to have been introduced or migrated recently through the Columbia River system from the northwestern United States: carp, northern black catfish, yellow perch, largemouth bass and the pumpkinseed (Carl and Clemens, 1948).

Except for the hatchery fish and the prickly sculpin, all species were captured by means of a small minnow seine. The sculpins were caught by angling, dip-net

and seine. The fish were transported to the Summerland Trout Hatchery, Summerland, B.C., in fry cans and then placed in rearing troughs or cement ponds depending upon the availability and convenience of holding space. The temperature of the hatchery supply of artesian water was 11°C.

As the lake temperatures were slowly rising during the period of fish captures, the temperatures at the time of capture are considered to be uppermost till that date. Certain limnological characteristics of Okanagan lake for an earlier season were determined by Clemens, Rawson and McHugh (1939).

Temperature of the body of water in which the fish were captured was above that of the hatchery supply in all cases except for the Kamloops trout (see Table I). No allowance was made for the possibility that there may have been some selection of captured fish by transfer from higher temperature to 11°C.

Other than for the Kamloops trout, no effort was made to feed the fishes during captivity although often supplies of dead trout eggs and ground mammalian liver were liberated by hatchery attendants into the holding tanks. Usually the carp, pumpkinseed, perch, suckers and silver-grey minnows did not feed. The sculpins ate trout eggs and would occasionally feed upon their own kind. The northern black catfish ate liver. The effect of starvation on upper lethal temperatures was not determined.

Species of fish which showed signs of deterioration (external sores, etc.) during captivity were the largemouth bass, yellow perch, northern black catfish and the carp. When signs of increased mortality appeared, the experiments were abandoned or a new lot obtained for study.

The method used in determining upper lethal temperatures was that developed by Brett (1941, 1944) and Fry *et al.* (1942) which method was adapted from that used earlier by Hathaway (1927). Four to six samples of fish were placed directly from the holding tank to the experimental tank of water at the desired temperature. The upper lethal temperature was taken as the temperature at which 50 per cent of the sample survived 24 hours. Usually this point was taken from a graph constructed for the percentage of those that survived 24 hours exposure plotted against the temperature of the test bath.

Two sizes of experimental tanks were used, 61 × 61 × 17.8 cm. (24 × 24 × 7 inches) and 76 × 76 × 20.3 cm. (30 × 30 × 8 inches). The construction was of galvanized sheet metal, coated completely with aluminum paint. The tanks were filled to within an inch of the top. The water was heated by stainless-steel electrical heaters purchased from the American Instrument Company. During the first six weeks the temperature was controlled by Fenwal thermostat switches suitably covered with stainless steel. During the last five weeks mercury-in-glass thermoregulators, Elektran transformers and mercury relays purchased from the American Instrument Company were used. The water was stirred by aeration, using Thiberg aerators and stone air-breakers purchased from the General Biological Supply House. Usually three to five tanks were in operation simultaneously.

The larger-sized sheet-metal tanks were used for samples of six larger fish or ten of the fingerling size. Each tank was covered with galvanized netting

0.64 × 0.64 cm. (¼ in.) mesh to prevent escapement. The tanks were well illuminated.

The temperature was recorded from time to time during each test run using laboratory-grade mercury thermometers calibrated from −10° to 110°C. A second check was made on the temperature by using Taylor maximum-minimum thermometers. The laboratory thermometers were standardized against a certified thermometer.

Source of the hatchery water supply is from an artesian well. Temperature of the water was uniform varying only 0.5°C. from 11.0°C. While the level of dissolved oxygen was adequate, the content of free carbon dioxide was relatively high (8 mm. Hg. or 30 p.p.m.). Aerators were added as required to the lethal test tanks in order to maintain oxygenation above 100 mm. Hg. (two-thirds saturated).

Usually the fish were removed from the tank as they died so as to reduce fouling of the water. Experimental tanks were cleaned after each experiment. At the conclusion of each test, all survivors were sacrificed for sex determination and search for parasites.

As was the experience of Brett (1944) and Fry *et al.* (1946), no difficulty was encountered in recognizing the end-point of life in the upper lethal-temperature tests. An exception to this rule was the indeterminate end-point for the first lot of carp.

TABLE II. Summary of upper lethal temperature data for freshwater fishes studied at the Summerland Trout Hatchery from May to July, 1951. The data are arranged in groups according to the approximate acclimatization temperatures. The values marked * are actual readings for 50 per cent mortality.

Species	Approximate acclimatization temperature	Upper temperatures at which fish survive 24 hours		
		All	50%	None
	° C.	° C.	° C.	° C.
Kamloops trout (fingerling)	11	22.4	24.0	25.7
Fine-scaled sucker	14	26.4	26.9*	28.3
Chub	14	24.4	27.1	29.1
Silver-grey minnow	14	25.2	28.3	28.3–31.1
Redside shiner	14	22.8	27.6	30.3
Prickly sculpin	18–19	22.8	24.1	26.5
Coarse-scaled sucker	19	25.7	29.4	32.2
Largemouth bass	20–21	25.2	28.9*	30.4
Squawfish	19–22	26.4	29.3	32.0
Northern black catfish	23	34.4	35.0	36.7
Yellow perch	22–24	28.9	29.2	29.1–29.8
Pumpkinseed	24	29.2	30.2	31.0
Carp	26	34.1	35.7	36.9

RESULTS

Results are presented in summary in Tables I–III and illustrated in Figures 1–14. Complete tables of data are appended to typescript reports which are on file in the libraries of research stations of the Fisheries Research Board of Canada.

The degree of variation for the upper lethal temperatures is not given. However, the variation during the test run is discussed below. The writer contends
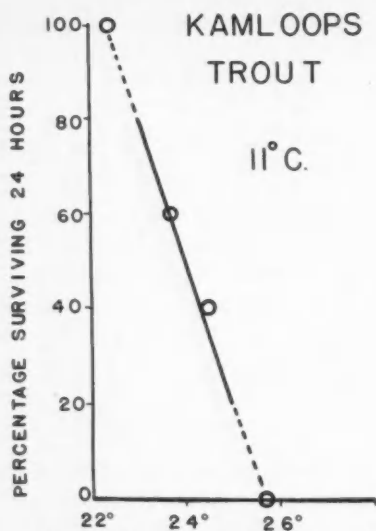
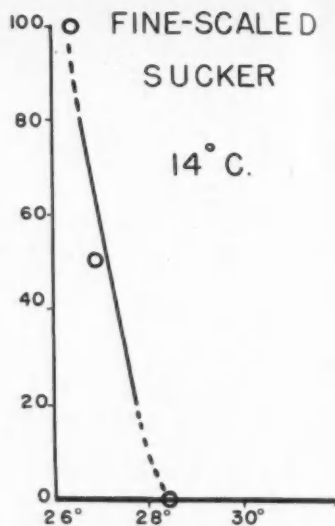FIGURE 1. Upper lethal temperature data for Kamloops trout fingerling acclimatized at 11°C.

FIGURE 2. Upper lethal temperature data for fine-scaled sucker acclimatized at approximately 14°C.
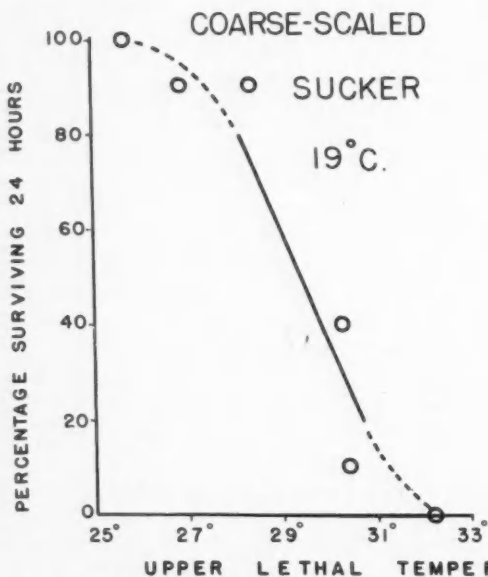

FIGURE 3. Upper lethal temperature data for coarse-scaled sucker acclimatized at approximately 19°C.
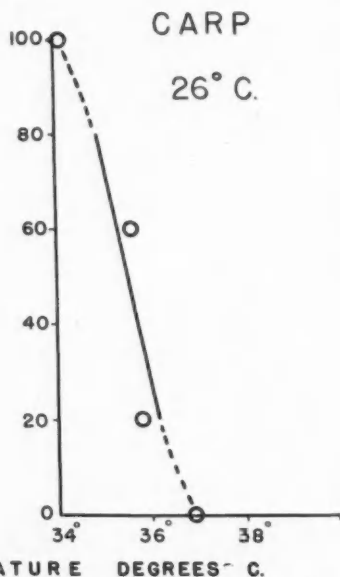

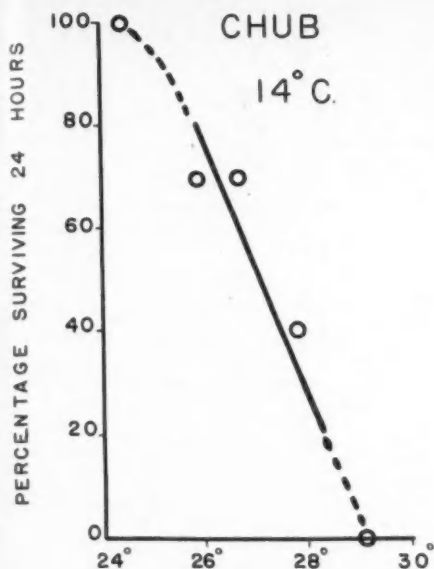FIGURE 4. Upper lethal temperature data for carp acclimatized at approximately 26°C.

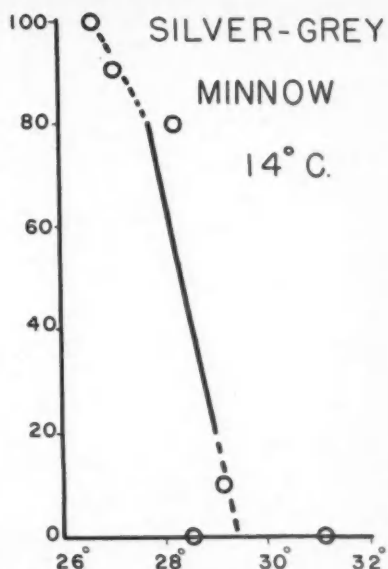FIGURE 5. Upper lethal temperature data for chub acclimatized at approximately 14°C.

FIGURE 6. Upper lethal temperature data for silver-grey minnow acclimatized at approximately 14°C.
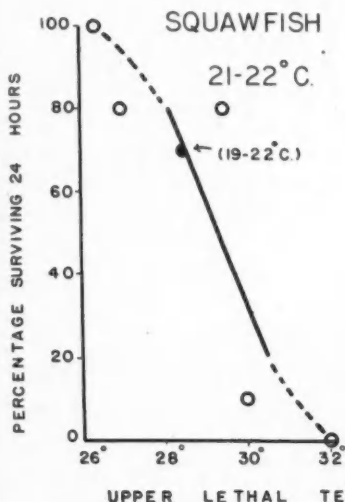
FIGURE 7. Upper lethal temperature data for squawfish acclimatized at approximately 19–22°C.
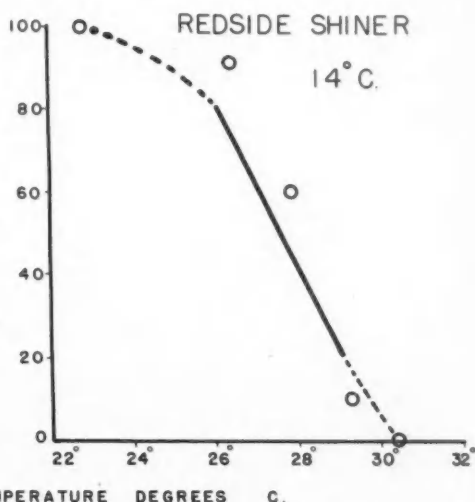
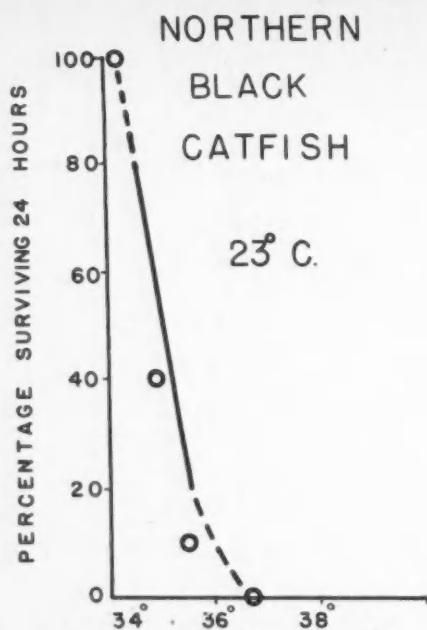FIGURE 8. Upper lethal temperature data for redside shiner acclimatized at approximately 14°C.

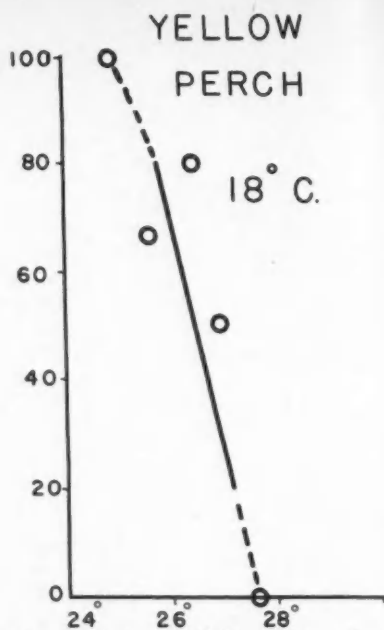FIGURE 9. Upper lethal temperature data for northern black catfish acclimatized at approximately 23°C.

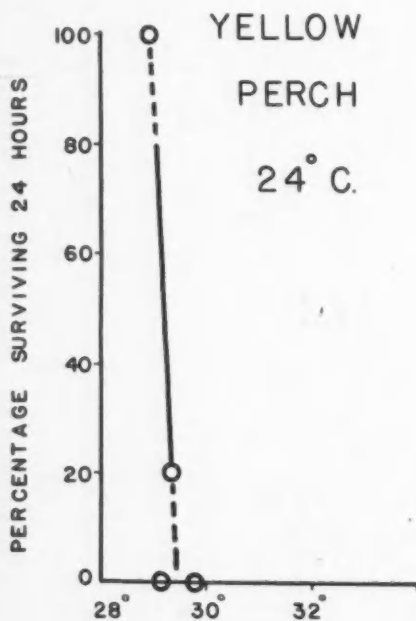FIGURE 10. Upper lethal temperature data for yellow perch acclimatized at approximately 18°C.

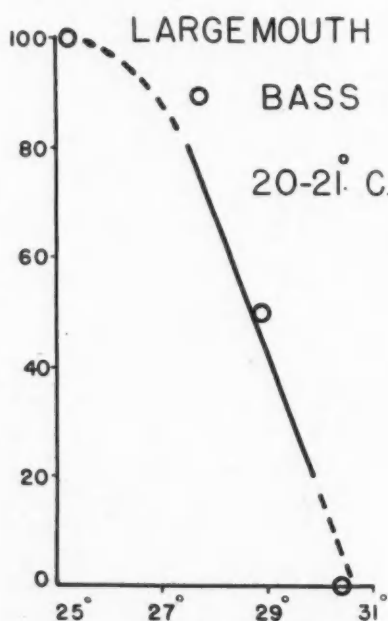FIGURE 11. Upper lethal temperature data for yellow perch acclimatized at approximately 24°C.

UPPER LETHAL TEMPERATURE DEGREES C.

FIGURE 12. Upper lethal temperature data for largemouth bass acclimatized at approximately 20–21°C.
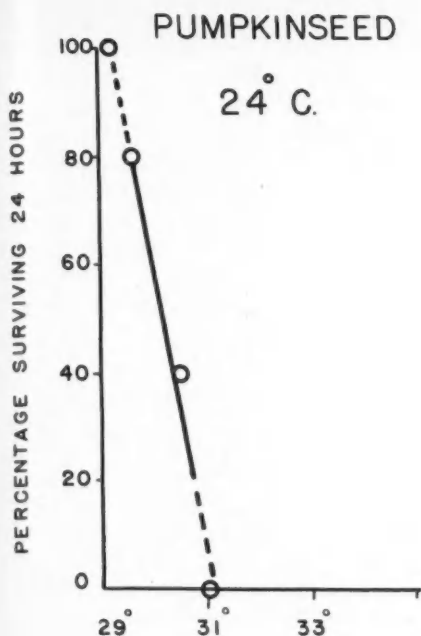
FIGURE 13. Upper lethal temperature data for pumpkinseed acclimatized at approximately 24°C.
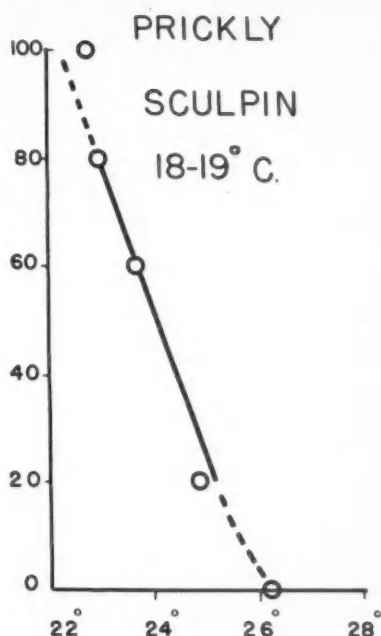
FIGURE 14. Upper lethal temperature data for prickly sculpin acclimatized at approximately 18–19°C.

that insufficient data are available to warrant placing limits upon the upper lethal temperatures. Possibly the most reliable limits would be the temperature at which all survive 24 hours exposure as the lower limit, and the temperature at which none survive within 24 hours as the upper limit (Table II). For a complete discussion of the implications of temperature variations, the reader is referred to the comprehensive discussions by Fry (1947) and Hart (1952).

DISCUSSION

SOURCES OF ERROR

For a systematic consideration of the sources of error encountered in determining lethal temperatures in fishes, the reader is referred to the recent works of Brett (1951) and Hart (1952).

From the publications of Hathaway (1927), Doudoroff (1942, 1945), Brett (1944, 1951), Fry et al. (1942, 1946) and Hart (1947), it is manifest that the greatest single factor bearing upon the validity of the lethal temperature data is the temperature of acclimation or acclimatization. In this study only an approximation of the acclimatization temperature can be given, except for the Kam-

loops trout, which were raised in the hatchery at a constant temperature. The value given for the acclimatization temperature for the other species is the day-light surface temperature for the time that the species was captured. Often temperatures were taken simultaneously at depths of 1–2 meters from the surface, but in no instance was the temperature at this depth more than 2°C. colder than that obtained at the surface. It is probable that the fish inhabited water the average temperature of which was lower than the daylight surface temperature. However as the temperature-acclimation rate is about 20-fold faster in the upward direction than downward (Brett, 1946; Doudoroff, 1942), the upper temperature affords the safer index to the acclimatization temperature.

The limitations to using the daylight surface temperature are shown in Table III. The upper lethal temperature for the chub was found to be 27°C. in 1950 and 1951, yet the daylight surface temperature at the time of capture was 10°C. on June 19, 1950, and 14°C. on June 17, 1951. A similar situation holds for the fine-scaled sucker, where the upper lethal temperature (27°C.) is the same for both years and yet the daylight surface temperature at the time of capture was 11.5°C. on May 25, 1950, and 14°C. on May 23, 1951. However, the upper lethal temperature for the redside shiner was found to be 25°C. during 1950 when the fish were captured at 9–11°C. on May 19–25, and 27.6°C. for a daylight surface temperature of 14°C. when captured on May 22–30, 1951. Again, the upper lethal temperature for Kamloops trout fingerlings was 24°C. at an actual acclimatization temperature of 11°C. for both years.

TABLE III. Summary of upper lethal temperatures for fishes studied at the Summerland Trout Hatchery during the summers of 1950 and 1951. The data for 1950 are taken from unpublished results of Black and Black (1950). The values marked * are actual readings for 50 per cent mortality.

Species	Year	Approximate acclimatization temperature	Upper lethal temperature (temperature at which 50% of fish survive 24 hours)
		° C.	° C.
Chub	1950	10	27
	1951	14	27.1
Redside shiner	1950	9–11	25
	1951	14	27.6
Kokanee (fry)	1950	11	22
Kamloops trout (fingerling)	1950	11	24
	1951	11	24.0
Fine-scaled sucker	1950	11.5	27
	1951	14	26.9*
Silver-grey minnow	1951	14	28.3
Yellow perch	1951	18	26.5*
		22–24	29.2
Pumpkinseed	1951	18	28.0
		24	30.2
Prickly sculpin	1951	18–19	24.1
Coarse-scaled sucker	1951	19	29.4
Largemouth bass	1951	20–21	28.9*
Carp	1951	20	31–34
		26	35.7
Squawfish	1951	19–22	29.3
Northern black catfish	1951	23	35.0

A second limitation to the study is the fact that the fish were held at a temperature of 11°C. from the time of capture till the time the lethal temperature experiments were carried out. Two influences may be operative to invalidate the reliability of the acclimatization state. In the first place there is the possibility that the hatchery temperature of 11°C. may be lethal at the lower level to some species plunged into the cooled fry cans and later transferred to the hatchery trough. In this case the sample of fish would constitute a selected sample. However, the mortalities immediately following capture were insignificant except for the yellow perch and pumpkinseed. From Hart's (1947) data it would appear that the lower lethal temperature for the yellow perch is below the temperature used here, namely 11°C.

Another possible influence following the transfer of the captured fishes to the hatchery water is that downward acclimation may have occurred before the lethal tests were completed. It would appear from the first set of data for the carp that such a process may have taken place. However the samples of pumpkinseed and yellow perch captured at different acclimatization temperatures appear to be stable. This appearance of stability for the latter two species may be deceptive, and merely reflect selection provided by the initial mortalities when the fish were first brought in from the field after capture.

A different limitation to the study is the possible adverse effect of the high level of free carbon dioxide content of the hatchery water supply, especially to fishes known to be sensitive to carbon dioxide. The dissolved carbon dioxide would be minimal in the test tanks which were always aerated previous to and during the test run.

When the results obtained at Summerland for the yellow perch at acclimatization temperatures of 18° and 22–24° are compared with those of Hart (1947), it would appear that the combined effects of exposure to holding in water of relatively high free carbon dioxide concentration and lowered temperature did not seriously impair the results. This contention implies that the stock of fish used by Hart in Ontario and the author in British Columbia were identical, and further, that the fish were in the same condition, factors which obviously are not known. The possible influences of free carbon dioxide and duration of preliminary exposure to lowered temperatures on the upper lethal temperature characteristics remain to be determined.

In a recent paper Brett (1951) has emphasized the place of proper feeding prior to lethal temperature test runs for members of the genus *Oncorhynchus*. This is possible for fish that will feed under the conditions of captivity. As mentioned earlier, none of the fish appeared to feed except the Kamloops trout, the prickly sculpin and the northern black catfish. The only published evidence on the possible effects of starvation on lethal temperature has been that of Brett (1944) for the brown catfish where no effect could be demonstrated. This evidence does not preclude the possibility that starvation may influence the lethal temperature runs for other species.

The effects of sex, size and age upon upper lethal temperatures were not determined in this study. Hart (1947) reported that there was no correlation

between size or age and the order of death at a given temperature. Later Hart (1952) found small differences in lethal temperatures associated with differences in age and size for three of 15 species studied.

The length of time that observations were carried out in each test was 24 hours, provided there were survivors. Fry *et al.* (1942) used a 14-hour period; Brett used a 12-hour period for work published in 1944 and a 48-hour period for much of his work reported in 1951, although periods up to seven days were also used. Hart (1947) used periods up to 8,000 minutes for upper lethal tests. No efforts were made in the study reported here to determine the least time which would approximate "infinity" so far as survival is concerned.

During most lethal test runs the temperature varied considerably as compared with the fine margin of variation (within $\pm 0.1°C.$) for the experiments of Brett (1944, 1951), Fry *et al.* (1942, 1946) and Hart (1947, 1952). For the data reported here, 75 per cent of the readings showed variations of $\pm 0.7°C.$ or less. In 7 per cent of the readings the temperature was $+1.0°$ to $+1.4°C.$ Seven per cent of the readings showed variation between $-1.1°$ and $-1.2°C.$ Two readings showed variations of $-2.0°$ to $-2.3°C.$ A maximum-minimum thermometer was used in most cases as a check on the control of temperature. In most instances, the readings are concordant with the observation for the laboratory thermometers after the corrections had been applied to the latter. The total spread for 49 readings was $2.3°$ or less; 7 at $2.6°$ to $2.9°$; 4 at $3.3°$; 1 at $4.4°$; and 1 at $4.5°C.$

ACCLIMATIZATION TEMPERATURE AND UPPER LETHAL TEMPERATURE

As noted above, the upward shift of the upper lethal temperature with increased temperature has been demonstrated by earlier workers (Doudoroff, 1942, 1945; Fry *et al.*, 1946; Brett, 1944 and 1951; Hart, 1947, 1952). In limited studies made this year on field acclimatization, the yellow perch, pumpkinseed and carp show higher lethal temperatures for fish captured at higher environmental temperatures later in the summer (Table II). Hart (1947) noted that the upper lethal temperature for yellow perch acclimatized to $25°$ was $29.7°$, and implied that this was the upper limit to which this species could be acclimated. The upper lethal temperature reported in this paper for the yellow perch is 29–$30°C.$ for an approximate acclimatization temperature of 22–$24°C.$ Brett obtained $30.9°$ as the upper lethal temperature for the same species acclimatized to 25–$26°$ in the field.

COMPARISON OF UPPER LETHAL TEMPERATURES FOR THE OKANAGAN SPECIES

The effect of the temperature history is so important to an evaluation of lethal temperature data that only limited comparisons are possible.

From 1950 data (Black and Black, 1950), the kokanee fry showed the lowest upper lethal temperature at $22°$ when acclimatized to $11°C.$ At the same approximate acclimatization temperature, the upper lethal temperatures for the

Kamloops trout, redside shiner, fine-scaled sucker and chub were 24°, 25°, 27° and 27°C. respectively.

The largemouth bass acclimatized to 20–21°C. has an upper lethal temperature of 28.9°C.

The squawfish acclimatized to 19–22°C. has an upper lethal temperature of 29.3°C.

In the acclimatization range of 22–24°C. the upper lethal temperatures for the yellow perch, pumpkinseed and northern black catfish are 29.2°, 30.2° and 35.0°C. respectively.

The highest acclimatization temperature was 26° for the carp, under which conditions this species showed the highest upper lethal temperature at 35.7°C.

TABLE IV. Comparison of upper lethal temperatures for some fishes studied in Ontario by Brett (1944), Fry *et al.* (1946), and by Hart (1947, 1952) in Ontario and the United States, with results reported for British Columbia freshwater fishes by Black and Black (1950) and in this paper. Values marked * were interpolated from graphs.

Family and species	Approximate acclimatization temperature	Upper lethal temperature	Authority
	° C.	° C.	
Family SALMONIDAE			
Kokanee fry (*Oncorhynchus nerka kennerlyi*)	11	22	Black & Black (1950)
Kamloops trout fingerlings	11	24.0	This paper
Speckled trout fingerlings (*Salvelinus fontinalis*)	11*	24*	Fry *et al.* (1946)
Family CATOSTOMIDAE			
Fine-scaled sucker	14	26.9	This paper
Coarse-scaled sucker	19	29.4	This paper
Common sucker (*Catostomus commersoni*)	20	30.0	Hart (1947)
	25–26	31.2	Brett (1944)
Family CYPRINIDAE			
Carp	26	35.7	This paper
Goldfish (*Carassius auratus*)	26*	36.6*	Fry *et al.* (1942)
Silver-grey minnow	14	28.3	This paper
Black nose dace (*Rhinichthys atratulus*)	15	29.6	Hart (1947)
Family AMEIURIDAE			
Northern channel catfish (*Ictalurus lacustris*)	20	32.7	Hart (1952)
	25	33.7	Hart (1952)
Brown catfish (*Ameiurus nebulosus*)	22.6	35*	Brett (1944)
Northern black catfish	23	35.0	This paper
Family PERCIDAE			
Yellow perch (summer)	25–26	30.9	Brett (1944)
(summer)	22–24	29–30	This paper
(summer)	25	29.7	Hart (1947)
(winter)	25	32.5	Hart (1952)
Family CENTRARCHIDAE			
Largemouth bass (B.C.)	20–21	28.9	This paper
Largemouth bass (Florida)	20	31.8	Hart (1952)
Largemouth bass (Ohio)	20	32.5	Hart (1952)
Pumpkinseed	25–26	34.5	Brett (1944)
	24	30.2	This paper
Bluegill (*Lepomis macrochirus*)	20	31.5	Hart (1952)
	30	33.9	Hart (1952)

COMPARISON OF UPPER LETHAL TEMPERATURES OF SOME OKANAGAN AND
SOUTHERN FISHES STUDIED IN ONTARIO AND EASTERN UNITED STATES

The Kamloops trout and speckled char (Fry *et al.*, 1946) have the same upper lethal temperature at 24°C., while that of the kokanee is somewhat lower at 22°C. (Table IV). The data for the three species of suckers are concordant when the acclimation (acclimatization) temperatures for the respective values are considered.

While data have been secured for more than four species of minnows, only values for the carp and the goldfish (Fry *et al.*, 1946), which are a degree apart, and two species of *Rhinichthys* are given. The upper lethal for *R. atratulus* (Hart, 1947) is 1.3°C. higher than *R. falcatus* when the acclimation temperature is only 1° higher than the acclimatization temperature (Table IV).

Values for the two species of catfish *Ameiurus nebulosus* (Brett, 1944) and *A. melas melas* are the same at 35° for a difference in acclimatization (acclimation) temperature of 0.5°, while the upper lethal temperature of *Ictalurus lacustris* (Hart, 1952) would appear to be a degree lower (Table IV).

Observations on the yellow perch obtained by the three authors are very close, differing by 1–2° at most (Brett, 1944; Hart, 1947, 1952).

Hart (1952) found that the upper lethal temperature for the largemouth bass exhibited the greatest spread in geographic variation. The value reported in this paper is lower than either value listed by Hart for an equivalent temperature history (Table IV).

The reading for the Ontario pumpkinseed obtained by Brett (1944) is 4.3° higher than that for the Okanagan sample for an increase in acclimatization temperature of 1–2°. Values obtained by Hart (1952) for *Lepomis macrochirus* studied in Florida rest between the above figures. (Table IV).

CONCLUSION

As stated in the introduction, the purpose in undertaking this study was to make possible a comparison of upper lethal temperatures with carbon dioxide asphyxiation data for the same batch of each species studied in the Okanagan when acclimated to the same temperature. This comparison will be made and discussed in another paper on carbon dioxide asphyxiation of fishes.

The lethal temperature data are presented in the belief that, despite the limitations and deficiencies of the study, the results may be of interest and use to ecologists and physiologists. Exposures for periods up to 24 hours at upper lethal temperatures afford useful data in characterizing the viability of species. These data also provide first approximations of upper lethal temperatures for comparisons on taxonomic and geographic bases, and for physiological purposes.

Within the limitations, the data confirm the level of results obtained by other workers for three species. In addition, comparisons at the same acclimatization or acclimation temperatures for kindred members of six families studied by workers in Ontario and the United States of America showed similarities in upper lethal temperatures to species studied in British Columbia.

ACKNOWLEDGMENTS

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